MSL: a pattern language for engineering self-adaptive systems

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Abstract

In architecture-based self-adaptation of decentralized systems, *design patterns* have been introduced to ease the design of complex adaptation solutions that usually require the interaction of different MAPE-K (Monitor-Analyze-Plan-Execute over a shared Knowledge) control loops, each dealing with an adaptation concern of the managed system. Such MAPE patterns have been proposed by means of a graphical notation, but without a well-defined way to document them and to express the semantics of components interactions.

In this paper, we propose an approach to overcome these limitations. We present a domain-specific language, called *MSL* for *MAPE Specification Language*, to define and instantiate MAPE patterns and to give semantics to some semantic variation points of the equivalent graphical notation for MAPE pattern. We also provide a formal semantics of the language by means of *self-adaptive Abstract State Machines*, an extension of the Abstract State Machines (ASMs) formalism to model self-adaptation. Such semantics definition comes with an automatic transformation of MSL models into formal executable models, and opens to the possibility of performing rigorous analysis (validation w.r.t. the adaptation requirements and verification of adaptation properties) of MSL models. Moreover, we present our current results toward a (long-term) realization of an *MSL-centric framework*, where MSL is the notation of a modeling front-end, on top of richer and more specific modeling, analysis, and implementation back-end frameworks.

As proof of concept of our approach, we show the application of MSL and its formal support to a running case study in the field of home automation, by modeling an adaptive control of a virtual smart home developed with the OpenHAB runtime platform.

Keywords: Pattern-oriented modeling, architecture-based self-adaptation, MAPE-K pattern loops, self-adaptive ASMs, adaptive smart home systems

1. Introduction

Nowadays, software systems are expected to operate in uncertain and dynamic environments with highly changing operational conditions. *Self-adaptation* has been suggested as a viable and effective solution to deal with the increasing complexity, uncertainty and dynamics of these systems [1, 2, 3]. In this area, feedback control loops that monitor and adapt managed parts of a software system are widely accepted as a key architectural solution [4] to realize self-adaptation in software systems. According to the original definition of Kephart and Chess [3], we refer to these control schemas as MAPE-K (Monitor, Analyze, Plan, and Execute over a shared Knowledge) – or simply MAPE – feed-

back loops.

A single feedback loop is not enough to model the interactions of multiple concerns and aspects in large distributed systems, as outlined in [1]. To this end, multiple interacting MAPE loops with a decentralized control are needed to deal with several adaptation concerns. To this purpose, common design patterns of interactive MAPE loops have been proposed in the literature [5], together with a graphical notation for representing them. Instances of MAPE patterns capture the architectural view of the adaptation layer of self-adaptive systems, according to a precise design solution. Although graphical representation of patterns and their instances is able to express the structure of components interactions (who interacts with whom), it cannot express their operational semantics (how and in which order). Fixing interaction semantics is necessary when moving from such diagrammatic representation to a formal specification to be used for property verification. Formal models of self-adaptive systems are, indeed, fundamental to guarantee reliability and correctness of the adaptation logic, both at design time and at runtime [6]. Moreover, although for documentation purposes visual representation can facilitate comprehension, the use of a graphical notation usually negatively affects efficiency, effectiveness, and satisfaction of software developers when they perform analysis and modification tasks [7].

To overcome these limitations, we propose a domain-specific language, called *MAPE Specification Language* (MSL), for architecting self-adaptive systems by using MAPE patterns and their instances as first-class citizens; in addition, the language has constructs to fix some semantic variations in MAPE component interactions. MSL adopts the same modeling concepts of the MAPE graphical notation presented in [5], but it uses a textual notation. The rationale in this decision is that textual notations should scale better than visual ones with increasing system design size [7].

We also provide formal semantics to the MSL language in terms of the Abstract State Machine formal method [8]. Such semantic definition allows: (a) a(n automatic) transformation of MSL models of MAPE loops into formal executable models given in terms of *self-adaptive Abstract State Machines* (self-adaptive ASMs) [9], an extension of multi-agent ASMs to express self-adaptation; and (b) exploiting all the potentialities of a formal method to provide rigorous analysis (validation w.r.t. the

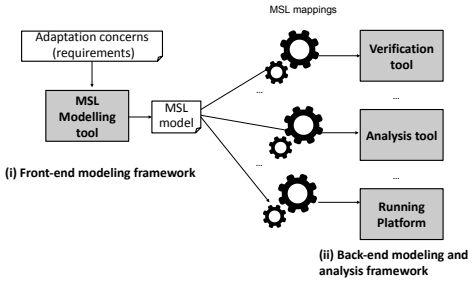


Figure 1: The envisioned MSL-centric framework

adaptation requirements and verification of adaptation properties) of MSL models.

Besides the goal of having a notation able to overcome the above mentioned limitations regarding scalability and semantic ambiguousness of the notation in [5], our long-term envision is that of providing a rigorous, but user-friendly, framework (illustrated in Fig. 1) centered around the usage of MSL for the engineering of self-adapting systems. We view the MSL modeling front-end to be on top of richer and more specific modeling, analysis, and implementation back-end frameworks. Following this rationale, MSL provides a concise and simple notation to design fast architectural solutions in terms of MAPE patterns and their instantiations. More specific models or code in target back-end frameworks/platforms could be synthesized from these MSL models by using model transformations, and then tailored/refined according to the target scope.

The automatic mapping from an MSL model into a self-adaptive ASM provides the bridge toward the ASM-based formal back-end framework. By exploiting model transformations, different other back-ends (e.g., UML-like modeling notations, other ADLs, formal methods, simulation platforms or quality evaluation tools) can be integrated into the MSL-centric framework.

A smart home automation system is considered throughout the paper as running example to show the applicability of MSL and how to specify components interaction semantics. In particular, we adopted OpenHAB[1] as the running platform for implementing the managed layer of a smart home whose adaptation/automation concerns have been modeled in MSL as instances of MAPE patterns. MSL models have been then refined at ASM level to capture the expected behavior of the MAPE components.

[1] `https://www.openhab.org`

A preliminary version of MSL has been presented in the conference paper [10]. With respect to [10], in this paper we provide (i) an extended description of the MSL language by providing the modelling of MAPE patterns (some taken from the literature [5] and other defined by the user), (ii) a precise semantics for MSL, (iii) an approach to re-design adaptation due to the results of a formal model analysis, (iv) a description of our (long-term) MSL-centric framework, and (v) a running case study in the field of home automation, by modeling an adaptive control of a virtual smart home developed with the OpenHAB runtime platform.

Paper organization. Some background on MAPE patterns for self-adaptation is given in Sect. 2. A presentation of the running case study is provided in Sect. 3. The MSL language is presented in Sect. 4 (including the language requirements and enginering approach, concrete and abstract syntaxes, parsing and validation), while its usage to model MAPE loops of the running case study is illustrated in Sect. 5. The MSL semantics in terms of a mapping from the MSL to the self-adaptive ASMs is described in Sect. 6. Some possible uses of an ASM-based framework, ASMETA, for formal analysis of MAPE loops of the running case study are presented in Sect. 7. Sect. 8 describes how the outcome of the formal analysis phase can lead to a re-design of the self-adaptive architecture if some faults and/or loops interferences are discovered. A description of our MSL-centric framework is given in Sect. 9. Sect. 10 discusses the assessment of MSL with respect to the language requirements. Sect. 11 discusses possible threats that may affect the validity of the approach. Sect. 12 provides a description of some related work. Sect. 13 concludes the paper and outlines some future directions of our work.

2. Background on MAPE-patterns for self-adaptation

In architecture-based self-adaptation, the system is usually separated into the *managed subsystem* – the actual system (both hardware and software) that interacts with the environment and whose behavior can be changed according to the stimuli from the environment and the adaptation concerns – and the *managing subsystem* that includes the adaptation logic whose aim is to fulfill the adaptation concerns. This logic is typically conceived as a set of interacting MAPE loops, one per each adaptation concern. In [5], some recurring structures of interacting MAPE components, *MAPE patterns*, have been defined for designing decentralized adaptation solutions, where controllers make independent decisions but have some kind of interaction. Fig. 2 shows an example of such a pattern (the *Aggregate* MAPE pattern), an instance of this pattern, and the key symbols of the graphical notation adopted in [5].

A MAPE pattern defines the structure of a composite MAPE loop as a set of *abstract groups* of MAPE components representing the roles of the feedback processes and the *type of interactions* between MAPE components. A *pattern instance* describes the structure of the pattern for one particular configuration. The annotated multiplicity of the interactions between the groups of MAPE components determines the allowed occurrences of the different groups in the pattern. Referring to Fig. 2, we can distinguish different types of interactions:

- *Managing-managed subsystem interactions* are those between M components and the managed subsystem for monitoring purposes, and between E components and the managed subsystem for performing adaptations.
- *Inter-component interactions* are those between different types of MAPE components. Typically, M interacts with A, A with P, and P with E.
- *Intra-component interactions* are those between MAPE components of the same type, e.g., interactions between M components.

Although it is undoubted the importance of MAPE patterns to represent known design solutions and support their reuse, the semantics of their graphical representation is often ambiguous and may intentionally leave *semantic variation points* (as in UML). Given the MAPE pattern in Fig. 2, elements of ambiguous interpretation are, for example, the AND/OR semantics of signals when an M computation of the higher MAPE group is triggered by the M computations of the lower groups. In MSL, we allow the specification of such semantic variations and support the designer in fixing the semantics at configuration level.

3. Running case study: adaptive control of a smart home

Smart home automation systems have been around for several years now [11]. However, designing them in a way that user well-being is guaranteed

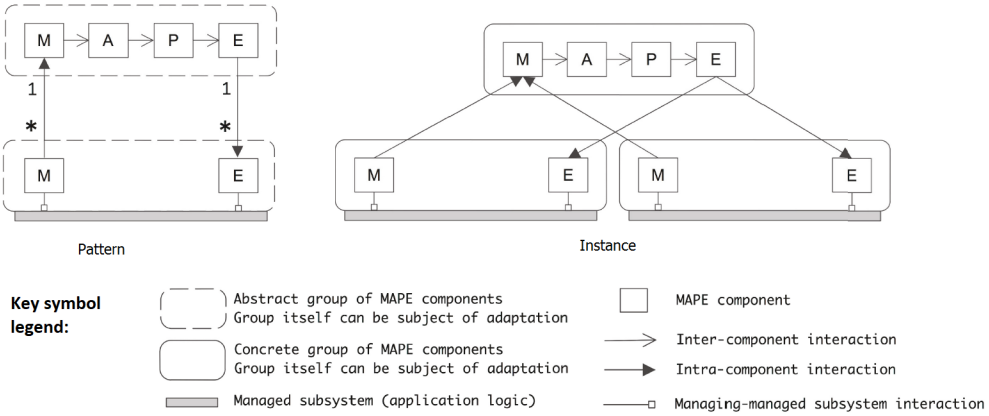


Figure 2: Aggregate MAPE pattern (left) and an instance of it (right) from [5]

in every situation is a very complex task. Typical real-life situations, indeed, involve conflicts that can arise in the home environment because, for example, unexpected events happen and/or because the home occupants are simultaneously engaged in different activities with different and discordant preferences for the home appliances.

Dealing with these situations require mechanisms that are able to handle unexpected and uncertain operational conditions. To this end, self-adaptive systems can offer the desired solution architecting the software control system of a smart environment with two layers: the managed layer, for basic control operations, and a managing layer realizing self-adaptation mechanisms for more advanced control operations/processes.

In this case study, the managed system has been modeled using the *Open Home Automation Bus* (OpenHAB)[2], which is an open source software platform for home automation. Being hardware/protocol agnostic, OpenHAB allows users to integrate and connect a variety of devices from classical home automation systems to new IoT gadgets and devices. Device (functionalities) are represented in terms of *items*, which have a *state* that can be changed by *commands*. A lightweight user-friendly dashboard interface for OpenHAB, the HABPanel, may be set up and made accessible from a standard web browser or smartphone/tablet. Through this dashboard, the user can observe values of the probes and the effectors of the smart home devices.

The managing system is conceived as a set of

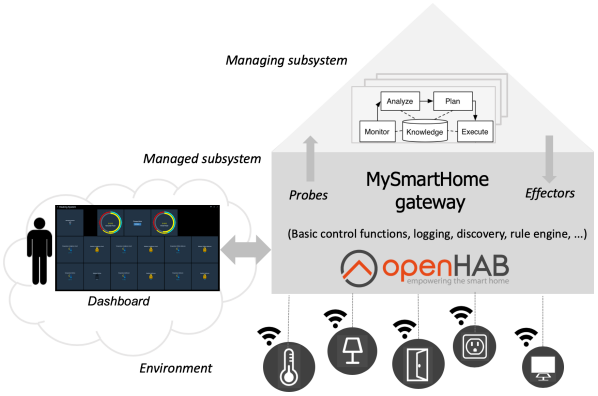


Figure 3: Self-adaptive architecture of the smart home control system

MAPE-K feedback loops to deal with several concerns and make the smart home gateway more robust. The structural architecture of our (virtual) smart home is illustrated in Fig. 3.

We configured the OpenHAB instance for a virtual smart home[3] as depicted in Fig. 4. The home is endowed with the devices necessary to run the automation processes presented in this article. The smart home is composed of two floors. Each floor has a smart thermostat communicating with different temperature sensors distributed among the rooms of the floor and with smart thermostatic valves ("smart radiator" in the figure) of the rooms heating of the floor. Air quality sensors, window opening control devices, and smoke/flame detectors are also present and configured as Thing's items of

[2] `https://www.openhab.org/`

[3] See the GitHub project `https://github.com/scandurra/VirtualSmartHome-Project`

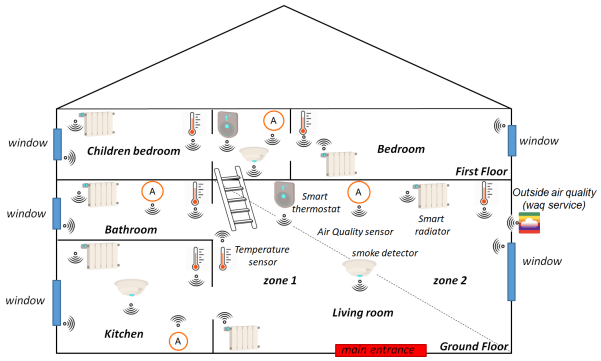


Figure 4: (Virtual) smart home example

interest in the OpenHAB platform.

Adaptation concerns. To cope with the design complexity, we separate the adaptation logic from the basic control system functionality and structure it in terms of MAPE-K feedback loops according to the following adaptation concerns. Note this list of concerns is only representative and used with the purpose of illustrating the MSL language.

Heating comfort (HC) At any time of the day, the system uses several room temperature sensors to achieve a high accuracy in the measures and regulates the heating at sufficient speed setting to ensure a comfortable temperature accordingly. Moreover, in order to minimize dispersion, the system holds windows closed when the heating is on.

Fire detection (FD) The system should detect and respond to the presence of a flame or a fire, allowing fire detection continuously.

Air quality (AQ) Air quality inside the home is at good level by opening/closing windows according to the measures provided by indoor air quality sensors and by an external web service for outdoor air quality.

These concerns might lead to (conflicting) sub-concerns and are also cross-cutting since they work on shared items and their implementation is distributed across multiple system modules. For this reason, they require modularization techniques and design patterns that define how they should relate to each other.

4. MSL: A DSL for MAPE patterns specification

MSL is a textual DSL for modeling the adaptation layer of a self-adaptive system.

The following subsections overview the main language requirements and development approach (Subsection 4.1), the MSL modeling constructs and concrete syntax (Subsection 4.2), and the MSL abstract syntax including parsing/validation aspects (Subsection 4.3). The MSL semantics is instead defined in Sect. 6 in terms of self-adaptive ASMs, while the status of the tools implementation around MSL is presented in Sect. 9.

4.1. MSL language requirements and engineering approach

To design the MSL language, we tried to adhere to proven design principles in software architecture [12] and DSL engineering [13] and, particularly, we identified the following set of requirements as key design dimensions of the language:

- *Model purpose*: The DSL is expected to be used as a modeling front-end to provide a concise and simple model of the composite structure of interactive MAPE-K loops, from which (for example, using model transformations/generators) a corresponding representation in a target back-end framework can be obtained and then tailored/refined according to the target scope (code implementation of MAPE components, formal behavior specification and analysis of MAPE-K loops, etc.), thus providing additional standalone independent models/code. The primary purpose of the model is therefore to serve as shared understanding of the MAPE-K loops structure between different solution spaces and associated frameworks/software platforms plugged-in the DSL-centric framework as back-end modules.
- *Separation of concerns*: Introduce language abstractions that allow dividing the adaptation logic of a self-adaptive software system into distinct adaptation concerns by structuring it into different MAPE loops with as little overlap in functionality as possible.
- *Principle of Least Knowledge (or Law of Demeter)*: A MAPE loop/component should not know about internal details of other MAPE loops/components. The advantage of following the Law of Demeter is that the resulting software tends to be more maintainable and adaptable.
- *Minimize upfront design*: Introduce language constructs allowing designing what is necessary, thus to avoid making a large design effort prematurely.

- *Pattern-oriented design*: Combine individual patterns of MAPE loops into heterogeneous compound structure of MAPE loops to facilitate a constructive development of the system's adaptation layer.
- *Model composability*: At a certain point of the design, models of MAPE-K loops obtained by separation of the adaptation concerns demand for model composition. To this end, a fundamental problem is assuring the ability to compose interfering MAPE-K loops to form dependable managing sub-systems without violating the desired adaptation requirements, and without diminishing the resulting trustworthiness.

Sect. 10 discusses the assessment of MSL with respect to these requirements.

Regarding the language engineering approach, we adopted the same concepts of the graphical notation introduced in Sect. 2 as core concepts of MSL for defining MAPE patterns and their instances. Additionally, further language constructs were added for modeling semantic variation points about MAPE component interactions explicitly. The MSL textual notation (the concrete syntax) has been developed using the grammarware approach of Xtext combined with the modelware approach of the Eclipse Modeling Framework (EMF); this allows the automatic generation of a model editor, a parser, and a basic validator. The Xtext grammar of the MSL notation together with the modeling/code artifacts of the running case study used in this article are available online at [14].

4.2. MSL modeling notation

Pattern definition Core modeling elements of MSL to define a MAPE pattern in terms of abstract groups of MAPE components, managed subsystems (i.e., a set of observable items/parts of a managed systems), and their interactions with multiplicities are reported in Fig. 5. For each element, the corresponding graphical notation adopted in [5] and the textual notation in MSL are shown. The MSL syntax is intuitive and self-explanatory.[4] Note that the MSL notation allows to be more specific than the graphical notation on some aspects; for example, the graphical notation used in [5] does not allow to distinguish between a single managed system and one composed of different subsystems, while this is possible in MSL: this is why the graphical notations of rows 2 and 3, and 4 and 5, are the same.

A MAPE pattern is defined by introducing a named element *abstract pattern* (by the keyword `abstract pattern`) that declares the managed subsystems' type, the abstract groups of MAPE components, and the type of interactions between MAPE components. Code 1 reports the MSL definition of a simple MAPE pattern (a single group of MAPE components), and Code 2 reports the MSL definition of the Aggregate MAPE pattern shown in Fig. 2. Code 3 shows the MSL definition of the Master-Slave MAPE pattern from [5] (on the top) and its corresponding MSL definition (on the bottom). All patterns proposed in [5] can be expressed in MSL and are available online (see the pattern library at [14]). Their description is briefly reported in Table 1.

Another (more complex) example of pattern definition is reported in Code 4. This pattern captures a hierarchical distribution control, where a higher-level MAPE group manages subordinate MAPE groups (i.e., the managed subsystems can be managing subsystems themselves). Specifically, it is an example of composition by hierarchy of known abstract patterns, aggregate MAPE and simple MAPE, that lead to a new abstract pattern. This abstract pattern will be used in Sect. 8 to compose and solve the two interfering concerns related to heating comfort and air quality, respectively, of the running case study.

Semantic variation points at interaction level One of the ambiguities of the MAPE loop representation proposed in [5] is related to the interpretation of the interactions [1,*], [*,1], and [*,*] among multiple components of different MAPE groups. Indeed, it is not clear whether, in order to trigger the interaction, the communication must be established among all the involved components or only some of them. Therefore, in MSL, in addition to the standard multiplicity 1, we allow the specification of the intended semantics of * by means of multiplicities *-ALL, *-SOME, and *-ONE (see, for example, interactions in Codes 2, 3, and 4). When used as source multiplicity of the interaction, these multiplicities respectively mean that the target group must receive the communication from *all* the interacting groups, from *at least one* of them, or from *exactly one* of them. In a similar way, when used as target multiplicity of the interaction, they mean

[4] Note that we do not provide keywords to distinguish between intra- and inter- interactions, since they are already characterized by the kind of MAPE components connected by the interaction.

MAPE element	Graphical notation	MSL notation

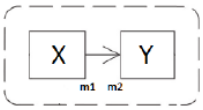
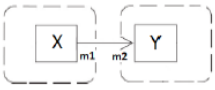
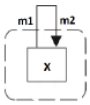
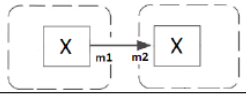
Abstract group AGrp of MAPE components		`group AGrp {`
		`  components M, A, P, E`
		`}`

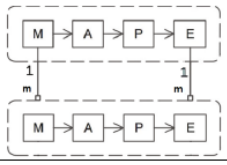
Managed system Sys		`system  Sys`

Managed system divided into subsystems Sys1, Sys2, etc.		`system  Sys1`
		`system  Sys2`
		`...`

Managing-managed interaction between an abstract group AGrp and a system Sys		`system Sys`
		`group AGrp {`
		`  managedSyS Sys`
		`  components M, A, P, E`
		`}`

Managing-managed interaction between an abstract group AGrp and subsystems Sys1, Sys2, etc.		`system Sys1`
		`system Sys2`
		`...`
		`group AGrp {`
		`  managedSyS Sys1,Sys2,...`
		`  components M, A, P, E`
		`}`

Inter-component interaction in an abstract group AGrp		`interaction AGrp.X -> AGrp.Y` `[m1,m2]`
Inter-component interaction between two abstract groups AGrp1 and AGrp2		`interaction AGrp1.X -> AGrp2.Y` `[m1,m2]`
Intra-component interaction in an abstract group AGrp		`interaction AGrp.X -> AGrp.X` `[m1,m2]`
Intra-component interaction between two abstract groups AGrp1 and AGrp2		`interaction AGrp1.X -> AGrp2.X` `[m1,m2]`

Managing-managed interaction between an abstract group AGrp0 and another abstract group AGrp1		`group AGrp1 {`
		`  components M, A, P, E`
		`}`
		
		`group AGrp0 {`
		`  managedGrp Agrp1 [m]`
		`  components M, A, P, E`
		`}`

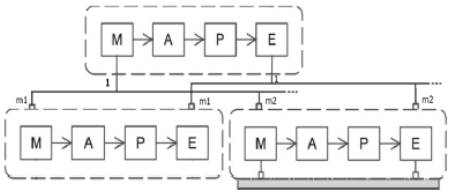
Managing-managed interaction between an abstract group AGrp0 and other abstract groups AGrp1, AGrp2, etc.		`system Sys`
		`group AGrp1 {`
		`  components M, A, P, E`
		`}`
		
		`group AGrp2 {`
		`  managedSyS Sys`
		`  components M, A, P, E`
		`}`
		`...`
		`group AGrp0 {`
		`managedGrp Agrp1[m1],Agrp2[m2],`
		`...`
		`  components M, A, P, E`
		`}`

Figure 5: MAPE pattern definition

that the source group must communicate with *all* the interacting target groups, a *non-empty subset* of them, or *exactly one* of them.[5] Note that in case of *-ALL, the MSL semantics does not specify *when* the different communications must be sent (in case it is used as target multiplicity) or received (in case it is used as source multiplicity): such *temporal semantics* will be provided by the corresponding ASM model. Similarly, also in case of *-SOME, and *-ONE, the MSL semantics does no specify *which ones*: the implementation of the *choice policy* will be specified in the ASM model.

Pattern instantiation Once defined, an abstract MAPE pattern can be instantiated by the designer

[5]If no multiplicity is reported, [1,1] is used as default.

Table 1: Description of the MAPE patterns proposed in [5]

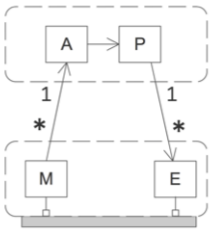
Pattern	Description
Aggregate	The whole adaptation decision is performed by a single centralized MAPE loop whose M component aggregates the information coming from different distributed M components, and the E component communicates with distributed E components to perform the adaptation.
Coordinated control	The four MAPE activities are decentralized over different loops. Each component of each loop coordinates with corresponding components in other loops.
Information sharing	It is similar to the coordinated control, but only M components of different loops interact with each other. The other components only communicate inside their loop.
Master-slave	The analysis and planning (A and P components) are performed in a single *master* loop, while monitoring and execution (M and E components) are distributed among different *slave* loops that communicate with the central master loop.
Regional planner	A *regional planner* is constituted of a loop performing the planning (P component) communicating with other local loops performing the other activities (M, A, and E components); a regional planner performs adaptation in the local *region*. Different regional planners can communicate through the P component of their region to coordinate adaptations that span different regions.
Hierarchical control	Different simple MAPE loops are provided for different concerns at different levels of abstraction. The MAPE loops are structured hierarchically, where the MAPE loops at the bottom interact with the managed subsystem, while MAPE loops at intermediated layers interact with the adaptation layers beneath. The top MAPE loop overviews the overall adaptation.

```
abstract pattern SimpleMAPE {
  system Sys

  group Main {
    managedSyS Sys
    components M, A, P, E
  }

  interaction Main.M -> Main.A
  interaction Main.A -> Main.P
  interaction Main.P -> Main.E
}
```

Code 1: Simple MAPE definition in MSL

```
abstract pattern AggregateMAPE {
  system Sys
  group Main {
    components M, A, P, E
  }
  group Interface {
    managedSyS Sys
    components M, E
  }
  interaction Interface.M -> Main.M [*-SOME,1]
  interaction Main.E -> Interface.E [1,*-SOME]
  interaction Main.M -> Main.A [1,1]
  interaction Main.A -> Main.P [1,1]
  interaction Main.P -> Main.E [1,1]
}
```

Code 2: Aggregate MAPE pattern definition in MSL




```
abstract pattern MasterSlaveMAPE {
  system Sys

  group Master {
    components A, P
  }

  group Slave {
    managedSyS Sys
    components M, E
  }

  interaction Slave.M -> Master.A [*-SOME,1]
  interaction Master.P -> Slave.E [1,*-SOME]
  interaction Master.A -> Master.P [1,1]
}
```

Code 3: Master-slave pattern definition in MSL

in an MSL model of her/his control loop architecture for a certain adaptation concern.

Code 5 shows the MSL model of the MAPE feed-

```
abstract pattern HierarchicalControlMAPE {
  system SysOne
  system SysTwo

  //Interface group for Aggregate MAPE
  group InterfaceOne {
    managedSyS SysOne, SysTwo
    components M, E
  }

  //Group for a Simple MAPE
  group InterfaceTwo {
    managedSyS SysTwo
    components M, A, P, E
  }

  //Main group for Aggregate MAPE
  group Intermediate {
    components M, A, P, E
  }

  //Higher group of the hierarchy
  group High {
    managedGrp Intermediate [*−ALL],
               InterfaceTwo [*−ALL]
    components A, E
  }

  interaction InterfaceOne.M −> Intermediate.M [*−SOME,1]
  interaction Intermediate.E −> InterfaceOne.E [1,*−SOME]
  interaction Intermediate.M −> Intermediate.A [1,1]
  interaction Intermediate.A −> Intermediate.P [1,1]
  interaction Intermediate.P −> Intermediate.E [1,1]
  interaction InterfaceTwo.M −> InterfaceTwo.A [1,1]
  interaction InterfaceTwo.A −> InterfaceTwo.P [1,1]
  interaction InterfaceTwo.P −> InterfaceTwo.E [1,1]
  interaction High.A −> High.E [1,1]
}
```

Code 4: A hierarchical control MAPE pattern definition in MSL

```
import AggregateMAPE
concrete pattern HC_MAPE
concretizationOf AggregateMAPE {
  system Heating: AggregateMAPE.Sys
  group MainHC: AggregateMAPE.Main
  group IntHC: AggregateMAPE.Interface
}
configuration MySmartHomeHC instanceOf HC_MAPE {
  hs_ff: HC_MAPE.Heating //heating system of First Floor
  hs_gf: HC_MAPE.Heating //heating system of Ground Floor

  //main group for the concern Heating Comfort
  main_hc: HC_MAPE.MainHC {
    components m_hc:M, a_hc:A, p_hc:P, e_hc:E
  }

  //interface group for the ground floor
  int_hc_gf: HC_MAPE.IntHC {
    managedSyS hs_gf
    components m_hc:M, e_hc:E
  }

  //interface group for the first floor
  int_hc_ff: HC_MAPE.IntHC {
    managedSyS hs_ff
    components m_hc:M, e_hc:E
  }

  //intra−interactions
  int_hc_gf.m_hc −> main_hc.m_hc
  int_hc_ff.m_hc −> main_hc.m_hc
  main_hc.e_hc −> int_hc_gf.e_hc
  main_hc.e_hc −> int_hc_ff.e_hc
  //inter−interactions
  main_hc.m_hc −> main_hc.a_hc
  main_hc.a_hc −> main_hc.p_hc
  main_hc.p_hc −> main_hc.e_hc
}
```

Code 5: MAPE loop for the Heating Comfort concern

back loop for the concern Heating Comfort of the running case study. It is an instance, by the `import` clause[6], of the aggregate MAPE pattern. A MAPE pattern instantiation consists of two phases: (i) *concretization* and (ii) *configuration*.

First, a *concrete pattern* (a named element preceded by the keyword `concrete pattern`) must be introduced as *concretization* of the abstract pattern to tailor the abstract pattern to a specific application domain. In this way, we ensure the structure of the pattern is the same, but we allow role renaming (i.e., the names of the abstract MAPE groups and managed subsystems) of the abstract pattern to reflect better the roles of the specific domain, and therefore the intended usage/reuse. Roles renaming is realized by *name binding*, i.e., through identifiers. The first part of Code 5 shows a concretization, called `HC_MAPE`, of the pattern `AggregateMAPE` for the concern Heating Comfort of the running case study.[7] Essentially, there is a concrete MAPE group, `IntHC`, that is responsible for monitoring rooms temperature via sensors and manages the heating subsystem (the managed subsystem) accordingly. So it plays the role of `Interface` w.r.t. the heating subsystem by providing both a component M and a component E. The group `MainHC` is responsible for realizing the adaptation concern; therefore, its component M aggregates temperature data from all temperature sensors through the components M of `IntHC`, and then its component A decides if it is necessary to adjust or not the heating settings. In case adaptation is required, components P and then E are triggered to plan adaptation actions and drive the components E of `IntHC`, respectively.

A concrete pattern is still at type-level, so to

[6] We allow the definition and instantiation of a MAPE pattern in the same MSL file with extension `.msl`. In order to create a library of patterns, we also allow the definition of patterns without instantiation, that can be later imported.

[7] All the developed MSL models and generated ASM models are available online at `https://github.com/fmselab/msl/tree/master/examples/SmartHomeGateway/`

bring it at instance-level it has to be instantiated for a specific scenario. To this purpose, a *configuration* (a named element introduced by the keyword `configuration`) must be introduced in the MSL model. Such a configuration instantiates the concrete groups of MAPE components and managed subsystems that effectively play the roles (as renamed) of the concrete pattern and their (concrete) interactions. The second part of Code 5 (as introduced by the keyword `configuration`) shows a configuration, called `MySmartHomeHC`, of the concrete pattern `HC_MAPE` for the smart home depicted in Fig. 4. In this configuration, there are two managed heating subsystems (`hs_gf` and `hs_ff`) for the two floors, Ground Floor (GF) and First Floor (FF), of the home, and their interface MAPE groups instances (`int_hc_gf` and `int_hc_ff`) interacting with one main MAPE group (`main_hc`).

Other examples of MSL models of MAPE feedback loops are reported in Sect. 5 to complete the specification of all the adaptation concerns of the running case study.

4.3. MSL abstract syntax, parsing, and validation

In Xtext, an EMF Ecore model (an object graph) is inferred automatically from the grammar of a language and then used as the in-memory representation of any parsed text file. Depending on the community, this in-memory object graph is called the abstract syntax tree (AST) or document object graph (DOM) or model instance of a metamodel (the classes typing the objects and their relationships). We use here the term (meta)model and AST interchangeably to denote the MSL abstract syntax that abstracts over syntactical information. The MSL metamodel as class diagram of Ecore `EClasses` is available online at [14].

The MSL metamodel is used by later processing steps in Xtext, such as validation, compilation or interpretation or artifacts/code generation. The MSL parser generated automatically by Xtext has been complemented, for example, by a validator to perform static analysis of MSL models and give informative feedback to the users. In particular, in addition to standard Xtext validation[8], we specified some constraints for pattern matching, i.e., to check whether a given pattern instance (configuration of a concrete pattern) conforms to its abstract pattern. We implemented such constraints using Xtend into the Xtext validator. The OCL formalization of two of these constraints is as follows:

- *Checking concrete systems in a concrete pattern w.r.t. the abstract pattern*: each concrete pattern must declare one concrete system per abstract system.
```
context Pattern
def: ap: AbstractPattern = self.absPattern
inv: ap.managedSystems?->forAll(
    as:AbstractSystem |
    self.managedSystems-->
    select(s:SystemBinding |
    s.absSys = as.name)-->size() = 1)
```
- *Checking concrete groups in a concrete pattern w.r.t. the abstract pattern*: each concrete pattern must declare one concrete group per abstract group.
```
context Pattern
def: ap: AbstractPattern = self.absPattern
inv: ap.abstractGroups?->forAll(
    ag:AbstractGroup |
    self.groups-->select(g:GroupBinding |
    g.absGroup = ag.name)-->size() = 1)
```

More complex constraints check that each interaction defined in the configuration must match in terms of source and target groups and source and target components, with the interactions defined in the abstract and concrete patterns.

5. MSL design of a smart home system

In order to model in MSL the adaptive control of our smart home environment, we first considered the adaptation concerns mentioned previously in Sect. 3 and organized them (see Table 2) by type of goal that adaptation would meet, by sources of uncertainty (that make adaptation necessary), and type(s) of adaptation to perform dynamically.

Below, we describe each concern and associated adaptation goal, and report the MSL models of the MAPE-K feedback loops that deal with these concerns.

5.1. Heating Comfort (HC)

For the concern HC, we aim at ensuring *heating comfort* by introducing a finer-grained control feature that adjusts the heating system at sufficient settings to allow regulation of radiators' valves (and, therefore, of the pump speed) depending on

[8] Xtext provides *syntactical validation* with the parser (to detect syntax errors), *cross-reference validation* with the linker (to detect broken links), and *concrete syntax validation* with the serializer (e.g., for type checking). Please refer to the Xtext documentation for more details: `https://www.eclipse.org/Xtext/documentation/303_runtime_concepts.html#validation`

Table 2: Adaptation requirements

Concern	Adaptation goal	Source of uncertainty	Type of adaptation
HC	Guarantee heating comfort	Variable heat necessity	Adjust heating at sufficient settings
		Some windows may be accidentally open	Hold windows closed when heating is on
FD	Guarantee fire detection sensing	Failure of fire/smoke detection sensors	Sensing functionality by exploiting other devices (e.g., heating sensors)
AQ	Guarantee air quality	Unpredictable air pollution levels	Hold windows closed/open

the real warm necessity accounted by the multiple room sensors, thus avoiding over- or under- heating. Moreover, in order to avoid warm dispersion, a hold-closed feature is added that keeps windows closed when heating is on.

The MSL MAPE feedback loop for this concern has been already presented in the previous Sect. 4 (see Code 5). We here refine it to separate the managed windows subsystem from the managed heating subsystem. To this purpose, the definition of the Aggregate MAPE pattern is also revised to allow for the specification in the concrete pattern of two types of managed subsystems (`Heating` and `Air`) denoting two different sets of managed items (heating and windows). Code 6 reports this extended MAPE loop pattern definition and its instantiation.

Note that MSL allows only to define the MAPE components and connectors constituting the control architecture, while the behavior of the modeled MAPE components (how to monitor, how to analyze the knowledge, etc.) should be specified by the developer using the implementation language of a target back-end platform integrated within the MSL framework. In Sects. 6 and 7, we describe, for example, how to formally specify the behavior of the MAPE components using the formalism of self-adaptive ASMs.

5.2. Fire Detection (FD)

With this concern FD, we aim at providing a more robust safety feature by guaranteeing *fire detection* sensing. Being a domestic environment, usually flame/smoke sensors detect the presence of fire or flames. If smoke/flame is detected by the sensors, the gateway notifies the user through an alarm and/or sends a message to the user smartphone. To guarantee fire detection, the managing system triggers the alarm even if none of the flame/smoke detectors switches to ON (e.g., they may be silent because of a failure) but a room temperature sensor reports a temperature greater than a certain threshold (e.g., $45°C$). This policy is an example of re-allocation of functionality on differently capable devices, typically used in IoT scenarios to allow architecting *emergent configurations* [15] when some devices may be silent (or failed). In our case, the fire sensing operation of a failed/silent fire/smoke sensor is temporarily realized by the temperature sensors in the home.

Code 7 reports the MAPE loop pattern for the concern FD as instantiation of the Master-Slave MAPE pattern. Being a domestic building, fire detection takes the form of a fire alarm system, incorporating three smoke devices in two zones (the two managed subsystems `fd_gf` and `fd_ff`): two in the kitchen and living room (ground floor), and one in the first floor between the two bedrooms. Two slave components `gf_slave` and `ff_slave` are responsible for monitoring rooms temperature and execution of alarms activation in the corresponding floors, while a (centralized) master component is responsible for the analysis and planning of proper actuation.

5.3. Air Quality (AQ)

With this concern AQ, we aim at guaranteeing a good *air quality* inside the home by providing a hold- open/close feature for windows to restore good air values depending on the indoor air sensors' measures. We assume an internal air quality index as measured by common indoor air sensors by aggregating different air parameters (CO_2, NO_2, CO, etc.) and evaluate it according to the classification levels of the `epa.gov` agency. We adopted the web service `www.aqicn.org` to obtain an air quality index for the air outside. This index is then evaluated according to the classification levels of the ARPA agency in Italy[9].

Code 8 reports the MAPE loop pattern for the concern AQ as instantiation of the simple MAPE pattern (a single group of MAPE components, as shown in Code 1). The air subsystem of a floor

[9] `http://www.arpalombardia.it`

```
abstract pattern AggregateMAPEplus {
  system SysOne
  system SysTwo

  group Main {
    components M, A, P, E
  }

  group Interface {
    managedSyS SysOne,SysTwo
    components M, E
  }

  interaction Interface.M -> Main.M [*-SOME,1]
  interaction Main.E -> Interface.E [1,*-SOME]
  interaction Main.M -> Main.A [1,1]
  interaction Main.A -> Main.P [1,1]
  interaction Main.P -> Main.E [1,1]
}

concrete pattern HC_MAPE
concretizationOf AggregateMAPEplus {
  system Heating: AggregateMAPEplus.SysOne //Heating sys
  system Air: AggregateMAPEplus.SysTwo//Windows sys
  group MainHC: AggregateMAPEplus.Main
  group IntHC: AggregateMAPEplus.Interface
}

configuration MySmartHomeHCplus instanceOf HC_MAPE {
  hs_ff: HC_MAPE.Heating //heating system of First Floor
  hs_gf: HC_MAPE.Heating //heating system of Ground Floor
  ws_gf: HC_MAPE.Air //windows system of Ground Floor
  ws_ff: HC_MAPE.Air //windows system of First Floor

  //main group for the concern Heating Comfort
  main_hc: HC_MAPE.MainHC {
    components m_hc:M, a_hc:A, p_hc:P, e_hc:E
  }

  //interface group for the ground floor
  int_hc_gf: HC_MAPE.IntHC {
    managedSyS hs_gf, ws_gf
    components m_hc:M, e_hc:E
  }

  //interface group for the first floor
  int_hc_ff: HC_MAPE.IntHC {
    managedSyS hs_ff, ws_ff
    components m_hc:M, e_hc:E
  }

  //inter-interactions
  main_hc.m_hc -> main_hc.a_hc
  main_hc.a_hc -> main_hc.p_hc
  main_hc.p_hc -> main_hc.e_hc
  //intra-interactions
  int_hc_gf.m_hc -> main_hc.m_hc
  int_hc_ff.m_hc -> main_hc.m_hc
  main_hc.e_hc -> int_hc_gf.e_hc
  main_hc.e_hc -> int_hc_ff.e_hc
}
```

Code 6: MAPE loop for the concern HC (extended)

```
import MasterSlaveMAPE
concrete pattern FD_MAPE
concretizationOf MasterSlaveMAPE {
  system FireDetection: MasterSlaveMAPE.Sys
  group MasterFD: MasterSlaveMAPE.Master
  group SlaveFD: MasterSlaveMAPE.Slave
}

configuration MySmartHomeFD instanceOf FD_MAPE {
  fd_ff: FD_MAPE.FireDetection // for First Floor
  fd_gf: FD_MAPE.FireDetection // for Ground Floor

//master
  fd_master: FD_MAPE.MasterFD {
    components a_fd:A, p_fd:P
  }

  //ground floor slave
  gf_slave: FD_MAPE.SlaveFD {
    managedSyS fd_gf
    components m_gf:M, e_gf:E
  }

  //first floor slave
  ff_slave: FD_MAPE.SlaveFD {
    managedSyS fd_ff
    components m_ff:M, e_ff:E
  }

  //interactions
  fd_master.a_fd -> fd_master.p_fd
  gf_slave.m_gf -> fd_master.a_fd
  ff_slave.m_ff -> fd_master.a_fd
  fd_master.p_fd -> gf_slave.e_gf
  fd_master.p_fd -> ff_slave.e_ff
}
```

Code 7: MAPE loop for the concern FD

```
import SimpleMAPE
concrete pattern AQ_MAPE
concretizationOf SimpleMAPE {
  system Air: SimpleMAPE.Sys
  group MainAQ: SimpleMAPE.Main
}

configuration MySmartHomeAQ instanceOf AQ_MAPE {
  aqs_gf: AQ_MAPE.Air //air system of Ground Floor
  aqs_ff: AQ_MAPE.Air //air system of First Floor

  aq_main: AQ_MAPE.MainAQ {
    managedSyS aqs_gf, aqs_ff
    components m_aq:M, a_aq:A, p_aq:P, e_aq:E
  }

  //interactions
  aq_main.m_aq -> aq_main.a_aq
  aq_main.a_aq -> aq_main.p_aq
  aq_main.p_aq -> aq_main.e_aq
}
```

Code 8: MAPE loop for the concern AQ

denotes a set of indoor air sensors, the windows system, and the outdoor air web service.

6. The MSL semantics

To provide formal semantics to the MSL language (whose abstract syntax can be defined in terms of a metamodel, that is inferred by Xtext), we here exploit the *semantic mapping* technique of the ASM-based semantic framework [16], which allows specifying the dynamic semantics of metamodel-based languages.

In the sequel, we first briefly introduce the se-

mantic technique (Sect. 6.1), then the formal computational model of self-adaptive ASMs [9] where the MSL constructs will take semantics (Sect. 6.2), and finally the mapping from an MSL model to a self-adaptive ASM (Sect. 6.3). Such mapping, besides specifying the language semantics, provides a bridge toward the ASM-based back-end framework ASMETA[10] (ASM mETAmodeling) [17] for formal analysis of MSL models.[11]

6.1. Semantic mapping technique

A metamodel-based language L has a well-defined semantics if a semantic domain S is identified and a semantic mapping $M_S : A \to S$ is provided [18] between the abstract syntax A (i.e., the metamodel of L) and S to give meaning to syntactic concepts of L in terms of the semantic domain elements. Although the semantic domain S and the mapping M_S can be described with varying degrees of formality, from natural language to rigorous mathematics, a clear and precise semantics requires both S and M_S to be defined in a formal way.

Sometimes, in order to give the semantics of a language L, another helper language L' can be used, with L' endowed with a well-defined semantic domain S' and semantic mapping M'_S. L' can be exploited to define the semantics of L by (1) taking S' as semantic domain for L, i.e., $S' = S$; (2) introducing a *building function* $M_B : A \to A'$ which associates an element of A' to every construct of A; (3) defining the *semantic mapping* $M_S : A \to S$ as $M_S = M'_S \circ M_B$. The function M_B can be built with different techniques [16].[12] We here exploit the *semantic mapping technique* where M_B is defined by using a model transformation language, and comes with a suitable tool that automatically applies M_B to any model m conforming to A in order to obtain a model m' conforming to A'.

Before applying the semantic mapping approach to define the semantics of the MSL language, we need to introduce the concept of *self-adaptive ASMs* that will play the role of the helper language.

[10] `http://asmeta.sourceforge.net/`

[11] The ASMETA toolset is just an example of all possible target back-end frameworks. Further details are given in Sect. 9.

[12] Note that we have renamed here the building function M in [16] with M_B to avoid misunderstanding with the monitor function M of a control loop.

6.2. Theoretical background on Self-Adaptive ASMs

ASMs [8] are an extension of FSMs where unstructured control states are replaced by states comprising arbitrary complex data (i.e., domains of objects with functions defined on them), and transitions are expressed by transition rules describing how data (state function values saved into *locations*) change from one state to the next. ASM models can be easily read as "pseudocode over abstract data" which comes with a well defined semantics: at each run step, all transition rules are executed in parallel by leading to simultaneous (consistent) updates of a number of locations.

By exploiting the notion of *multi-agent ASM* – where each agent executes its own ASM in parallel with other agents' ASMs and the agent's *program* is the set of all transition rules of its own ASM –, in [9] we provide the definition of *self-adaptive ASMs* as a multi-agent ASM where the set *Agents* is the disjoint union of the set *MgA* of *managing agents* and the set *MdA* of *managed agents*. Managing agents encapsulate the logic of self-adaptation, while managed agents encapsulate the system's functional logic. Still in [9], a MAPE loop (or interactive MAPE loops) for an adaptation concern *adj* is defined as:

$$MAPE(adj) = \left\langle R_{adj}, \xrightarrow{adj}, K(adj) \right\rangle \qquad (1)$$

R_{adj} is the set of transition rules, executed by managing agents, modeling the MAPE computations involved in the control loop; $\xrightarrow{adj}$ is a relation on R_{adj} and is used to express MAPE computations interaction (e.g., M infers an A, which infers a P, which infers an E); $K(adj)$ is the knowledge (part of the locations of the self-adaptive ASM) used to keep the information necessary to enact and coordinate MAPE computations.

By the interaction relation definition, we can express a *decentralized* and *centralized* execution schema (also a mixed schema is possible) among MAPE computations. In the decentralized schema, rules in R_{adj} are executed by different agents, which interact with each other *indirectly* by sharing locations of the knowledge $K(adj)$ – and, therefore, rules are executed in different run steps. In the centralized schema, rules in R_{adj} are executed by the same managing agent either *indirectly*, or *directly* where each rule invokes the rule it is in interaction relation with – and, therefore, all rules are executed in one step (*waterfall* style).

Table 3: Mapping from MSL models into Self-adaptive ASMs

MAPE element	**ASM construct**
Managed system *Sys*	Agent type `SysMda` with program `r_Sys` modeling its behavior
Managing group *Grp*	Agent type `GrpMga` with program `r_Grp` modeling its behavior
Component X ($X \in \{M, A, P, E\}$) of group *Grp*	Macro rule `r_GrpX` (called from program `r_Grp`) that models the behavior of component X. The rule contains a *placeholder* `<<TODO>>` for indicating that the designer must supply an implementation.
Decentralized interaction $Grp1.X \rightarrow Grp2.Y[m_1, m_2]$	Functions modeling the interaction among agents of `Grp1Mga` and `Grp2Mga`: - `fromGrp1toGrp2` associating agents of `Grp1Mga` to agents of `Grp2Mga`. The signature is `fromGrp1toGrp2: Grp1Mga -> Grp2Mga` if m_2=1, and `fromGrp1toGrp2: Grp1Mga -> Powerset(Grp2Mga)` if $m_2 \in$ {*-ALL,*-SOME,*-ONE}. - `fromGrp2toGrp1` associating agents of `Grp2Mga` to agents of `Grp1Mga`. The signature is `fromGrp2toGrp1: Grp2Mga -> Grp1Mga` if $m_1 = 1$, and `fromGrp2toGrp1: Grp2Mga -> Powerset(Grp1Mga)` if $m_1 \in$ {*-ALL,*-SOME,*-ONE}. - `sgnGrp1Grp2: Prod(Grp1Mga,Grp2Mga) -> Boolean` modeling the *signals* exchanged among agents in order to trigger the interaction.
Centralized interaction $Grp.X \rightarrow Grp.Y[1, 1]$	Components rules X, Y of the same group *Grp* are called in a waterfall style by the agent of type `GrpMga`
Variation point semantics of multiplicity $m_1 \in$ {*-ALL, *-SOME, *-ONE} in interaction $Grp1.X \rightarrow Grp2.Y[m_1, m_2]$	A derived function `startGrp2Y: Grp1Mga -> Boolean` (read in rule `r_Grp2Y`) is used to combine the different values of the signals going from `Grp1Mga` agents to a single `Grp2Mga` agent `$b`; function implementation depends on the variation point semantics: *-ALL: (**forall** $a **in** fromGrp2toGrp1($b) **with** sgnGrp1Grp2($a, $b)) *-SOME: (**exist** $a **in** fromGrp2toGrp1($b) **with** sgnGrp1Grp2($a, $b)) *-ONE: (**exist unique** $a **in** fromGrp2toGrp1($b) **with** sgnGrp1Grp2($a, $b))
Variation point semantics of multiplicity $m_2 \in$ {*-ALL, *-SOME, *-ONE} in interaction $Grp1.X \rightarrow Grp2.Y[m_1, m_2]$	Rule `r_Grp1X` of agent `Grp1Mga` sends signals to `Grp2Mga` agents. The selected Grp2Mga agents depend on the variation point semantics: *-ALL: to all associated agents *-SOME: to a randomly selected subset of agents: chooseone({$a **in** Powerset(Grp2Mga)\| not (isEmpty($a)): $a}) *-ONE: to a randomly selected agent: chooseone({$a **in** Grp2Mga:$a})
Concrete interactions in the **configuration** section	Declaration of agents, instances of agents types `SysMda` and `GrpMga`, and initialization of interaction functions `fromGrp1toGrp2` and `fromGrp2toGrp1`

6.3. Mapping MSL models into Self-Adaptive ASMs

Coming back to the semantic mapping technique introduced in Sect. 6.1, we here provide the definition of the building function M_B over MSL. As helper language, we assume the textual notation of the self-adaptive ASMs whose semantic domain and mapping are well defined [19, 9].

The function M_B applied to an MSL model generates a self-adaptive ASM.[13] Table 3 summarizes the mapping rules of the transformation process.

The agents set of the self-adaptive ASM is obtained by creating an agent in *MdA* for each managed system and an agent in *MgA* for each managing group of a concrete pattern.

The set of rules R_{adj} involved in the *MAPE* loop is built by creating a rule `r_GrpX` for each component X of each group *Grp*.

A decentralized interaction $Grp1.X \rightarrow Grp2.Y$ determines a relation between rules `r_Grp1X` and `r_Grp2Y` in $\xrightarrow{adj}$; the correct interaction between the two rules is obtained by creating, in the knowledge $K(adj)$, two functions, `fromGrp1toGrp2` and `fromGrp2toGrp1`, specifying the interacting agents, and a function `sgnGrp1Grp2` modeling the *signals* the agents use for establishing the communication. A centralized interaction between components X and Y of the same group *Grp* is obtained by directly invoking rule `r_GrpY` from `r_GrpX`.

The mapping also captures the desired semantics of * multiplicity; a source multiplicity of * kind is modeled by means of a formula (used as guard of a component rule) that requires that *all/some/exactly one* signal(s) must be received by the target agent in order to trigger the interaction. A target multiplicity of * kind, instead, is modeled by forcing the starting agent to write the signal to *all/some/exactly one* target agent(s). Note

[13] Details on how we validated M_B are reported in Sect. 11.

that we provide a default implementation of the choice of the target agents in case of *-SOME and *-ONE (i.e., they are selected randomly); however, the user should refine such choice with a more precise one, by considering the system requirements (see Sect. 7.1).

The generated self-adaptive ASM model is executable as coordination schema of MAPE components, but with empty implementation (marked by placeholders `<<TODO>>`) for component rules in R_{adj} (only standard writing and reading of signals is added to the model).

In order to model the behavior of the MAPE components performing a specific adaptation scenario, the generated ASM model has to be refined. This process is explained in Sect. 7.1.

Running example. As mapping example, Code 9 reports the ASM model (in the AsmetaL notation) generated automatically from the MSL model shown in Code 6. According to the framework of self-adaptive ASMs presented in Sect. 6.2 (see Eq. 1) and the resulting ASM in Code 9, the MAPE loop for the adaptation concern HC is defined as $MAPE(HC) = \left\langle R_{HC}, \xrightarrow{HC}, K(HC) \right\rangle$, where

R_{HC} = {r_IntHCM, r_IntHCE, r_MainHCM, r_MainHCA, r_MainHCP, r_MainHCE}
$\xrightarrow{HC}$ = {(r_IntHCM, r_MainHCM), (r_MainHCM, r_MainHCA), (r_MainHCA, r_MainHCP), (r_MainHCP, r_MainHCE), (r_MainHCE, r_IntHCE)}
$K(HC)$ = {fromIntHCMtoMainHCM, fromMainHCMtoIntHCM, sgnIntHCMMainHCM, fromMainHCEtoIntHCE, fromIntHCEtoMainHCE, sgnMainHCEIntHCE}

7. Behavioral refinement and formal analysis of the smart home MAPE loops

MSL is a lightweight formalism for representing MAPE patterns and their instances. These models can be automatically mapped into self-adaptive ASMs, according to the semantic mapping shown in Sect. 6.3.

Once the MSL models are mapped into ASMs, the whole set of tools of the ASMETA framework can be used to provide early feedback about the correct loops execution as devised in [9]. However, in order to capture the intended behavior of the components realizing the adaptation concern, these formal models must be refined, and the starting point of this model refinement process is to replace the placeholders automatically generated by the model transformation, with effective ASM rules specifying the M,A,P,E computations. Effort for this refinement is domain-specific and has to be done manually. Moreover, the designer can also refine the standard implementation of * multiplicity by selecting the set of agents from/to which the signals must be received/sent. Moreover, the designer can also specify *when* the signals must be sent/received (all together or asynchronously); note that (as we have already discussed in Sect. 4.2), such *temporal semantics* can not be specified in the MSL model and it can only be provided in the ASM model (thanks to the ASM operational semantics).

In this section, we first show a model refinement in order to completely specify a MAPE loop for an adaptation concern of the running case study, and then we show some possible uses of the ASMETA framework for formal analysis of the MAPE loops.

7.1. Model refinement

As an example of refinement, Code 10 reports an excerpt of the elements added in the refined model of the HC MAPE loop. A complete version of the ASM model for the HC concern is available online.

First, new signature elements (domains and functions) have been added to represent the knowledge for the OpenHAB items related to heating and windows of the managed home. For example, to accurately calculate how much heat is required to warm rooms, a monitored function `temperature` has been added to feed the model with the input temperature of the heated floors, i.e., the average value of all rooms temperature of a floor (as computed by the state aggregation function `AVG` for groups of numeric items in OpenHAB); indeed, in ASMs, monitored functions represent the inputs coming from the environment. The sensed temperature stored into the knowledge (by components M) is represented by a separate controlled function `temperature_Saved`. Similarly, for other sensed data.

Other knowledge functions have been added for the control process. For example, a function `desiredHeatingSetting` represents the adaptation decision made by component P, namely the heating speed mode for a floor (stopped, fairly hot, and very hot) chosen as final setting for the actuator in order to create enough heat and ensure the floor is heated as set on the floor's thermostat (the monitored function `temperature_Setpoint`). The final setting for

```
asm MySmartHomeHCplus
import StandardLibrary
signature:
  //HC_MAPE
  domain HeatingMdA subsetof Agent
  domain AirMdA subsetof Agent
  domain MainHCMgA subsetof Agent
  domain IntHCMgA subsetof Agent
  derived startMainHCM: MainHCMgA -> Boolean
  derived startMainHCA: MainHCMgA -> Boolean
  derived startMainHCP: MainHCMgA -> Boolean
  derived startMainHCE: MainHCMgA -> Boolean
  controlled heatingManagedByIntHC: IntHCMgA -> HeatingMdA
  controlled airManagedByIntHC: IntHCMgA -> AirMdA
  derived startIntHCM: IntHCMgA -> Boolean
  derived startIntHCE: IntHCMgA -> Boolean

  //I: IntHC.M -> MainHC.M [*-SOME,1]
  controlled sgnIntHCMMainHCM: Prod(IntHCMgA, MainHCMgA) -> Boolean
  controlled fromIntHCMtoMainHCM: IntHCMgA -> MainHCMgA
  controlled fromMainHCMtoIntHCM: MainHCMgA -> Powerset(IntHCMgA)

  //I: MainHC.E -> IntHC.E [1,*-SOME]
  controlled sgnMainHCEIntHCE: Prod(MainHCMgA, IntHCMgA) -> Boolean
  controlled fromMainHCEtoIntHCE: MainHCMgA -> Powerset(IntHCMgA)
  derived orSelectorfromMainHCEtoIntHCE: MainHCMgA -> Powerset(IntHCMgA)
  controlled fromIntHCEtoMainHCE: IntHCMgA -> MainHCMgA

  //MySmartHomeHC
  static hs_ff: HeatingMdA
  static hs_gf: HeatingMdA
  static ws_gf: AirMdA
  static ws_ff: AirMdA
  static main_hc: MainHCMgA
  static int_hc_gf: IntHCMgA
  static int_hc_ff: IntHCMgA

definitions:
  function startMainHCM($b in MainHCMgA) =
    (exist $a in fromMainHCMtoIntHCM($b) with sgnIntHCMMainHCM($a, $b))

  function startMainHCA($b in MainHCMgA) = true
  function startMainHCP($b in MainHCMgA) = true
  function startMainHCE($b in MainHCMgA) = true
  function startIntHCM($b in IntHCMgA) = true
  function startIntHCE($b in IntHCMgA) = sgnMainHCEIntHCE(fromIntHCEtoMainHCE($b), $b)

  function orSelectorfromMainHCEtoIntHCE($b in MainHCMgA) =
    chooseone({$a in Powerset(IntHCMgA) | not(isEmpty($a)): $a})

  rule r_Heating = skip //<<TODO>>

  rule r_Air = skip //<<TODO>>

  rule r_CleanUp_IntHCM = skip //<<TODO>>

  rule r_IntHCM =
    if startIntHCM(self) then
      par
        skip //<<TODO>>
        if not sgnIntHCMMainHCM(self,fromIntHCMtoMainHCM(self)) then
          sgnIntHCMMainHCM(self,fromIntHCMtoMainHCM(self)) := true
        endif
        r_CleanUp_IntHCM[]
      endpar
    endif

  rule r_CleanUp_IntHCE =
    sgnMainHCEIntHCE(fromIntHCEtoMainHCE(self), self) := false

  rule r_IntHCE =
    if startIntHCE(self) then
      par
        skip //<<TODO>>
        r_CleanUp_IntHCE[]
      endpar
    endif

  rule r_IntHC =
    par
      r_IntHCM[]
      r_IntHCE[]
    endpar

  rule r_CleanUp_MainHCM =
    forall $a in fromMainHCMtoIntHCM(self) do
      sgnIntHCMMainHCM($a, self) := false

  rule r_MainHCM =
    if startMainHCM(self) then
      par
        skip //<<TODO>>
        r_MainHCA[]
        r_CleanUp_MainHCM[]
      endpar
    endif

  rule r_CleanUp_MainHCA =
    skip //<<TODO>>

  rule r_MainHCA =
    if startMainHCA(self) then
      par
        skip //<<TODO>>
        r_MainHCP[]
        r_CleanUp_MainHCA[]
      endpar
    endif

  rule r_CleanUp_MainHCP = skip //<<TODO>>

  rule r_MainHCP =
    if startMainHCP(self) then
      par
        skip //<<TODO>>
        r_MainHCE[]
        r_CleanUp_MainHCP[]
      endpar
    endif

  rule r_CleanUp_MainHCE = skip //<<TODO>>

  rule r_MainHCE =
    if startMainHCE(self) then
      par
        skip //<<TODO>>
        forall $a in orSelectorfromMainHCEtoIntHCE(self) do
          sgnMainHCEIntHCE(self, $a) := true
        r_CleanUp_MainHCE[]
      endpar
    endif

  rule r_MainHC = r_MainHCM[]

  main rule r_mainRule =
    forall $a in Agent with true do
      program($a)

default init s0:
  function sgnIntHCMMainHCM($a in IntHCMgA, $b in MainHCMgA) = false
  function sgnMainHCEIntHCE($a in MainHCMgA, $b in IntHCMgA) = false
  function fromIntHCMtoMainHCM($a in IntHCMgA) =
    switch($a)
      case int_hc_gf: main_hc
      case int_hc_ff: main_hc
    endswitch

  function fromMainHCMtoIntHCM($a in MainHCMgA) =
    switch($a)
      case main_hc: {int_hc_gf, int_hc_ff}
    endswitch
  function fromMainHCEtoIntHCE($a in MainHCMgA) =
    switch($a)
      case main_hc: {int_hc_gf, int_hc_ff}
    endswitch
  function fromIntHCEtoMainHCE($a in IntHCMgA) =
    switch($a)
      case int_hc_gf: main_hc
      case int_hc_ff: main_hc
    endswitch
  function airManagedByIntHC($x in IntHCMgA) =
    switch($x)
      case int_hc_gf: ws_gf
      case int_hc_ff: ws_ff
    endswitch
  function heatingManagedByIntHC($x in IntHCMgA) =
    switch($x)
      case int_hc_gf: hs_gf
      case int_hc_ff: hs_ff
    endswitch

  agent IntHCMgA: r_IntHC[]
  agent HeatingMdA: r_Heating[]
  agent MainHCMgA: r_MainHC[]
  agent AirMdA: r_Air[]
```

Code 9: ASM model of the Heating Comfort (HC) MAPE loop

the actuator is realized by the component E by assigning the planned value to the function `heating_Setting` (read by the managed agent). This last is the value to send through an OpenHAB command (the actuator or effector) to the item `Heating_Setting_GF` or `Heating_Setting_FF`, depending on the floor, of the managed home. Similarly, a group of functions have been added for the hold-closed func-

```
asm MySmartHomeHCplus_refined
import StandardLibrary
signature:
...
  //domains added in refinement
  enum domain HeatingSetting = {FAIRLY_HOT | VERY_HOT | STOPPED}
  enum domain HeatingStatus = {ON|OFF}
  enum domain WindowStatus = {OPEN|CLOSED}
  domain Temperature subsetof Integer
...
  //functions added in refinement
  //knowledge for the managed smart home items (heating and windows)
  monitored temperature: HeatingMdA -> Temperature
  monitored temperature_Setpoint: HeatingMdA -> Temperature
  monitored temperature_Midpoint: HeatingMdA -> Temperature
  monitored windowsStatus: AirMdA -> WindowStatus
  monitored heatingStatus: HeatingMdA -> HeatingStatus
  controlled temperatureSaved: IntHCMgA -> Temperature
  controlled temperature_SetpointSaved: IntHCMgA -> Temperature
  controlled temperature_MidpointSaved: IntHCMgA -> Temperature
  controlled windowsStatusSaved: IntHCMgA -> WindowStatus
  controlled heatingStatusSaved: IntHCMgA -> HeatingStatus
  derived heatingsON: Boolean
  controlled desiredHeatingSetting: IntHCMgA -> HeatingSetting
  controlled desiredWindowsStatus: IntHCMgA -> WindowStatus
  derived computeHeatingSetting : IntHCMgA -> HeatingSetting
  controlled heating_Setting: HeatingMdA -> HeatingSetting
  controlled windows_Setting: AirMdA -> WindowStatus

  //Function for the coordination of the overall compound MAPE loop; they are
  //used to strictly sequence different executions of the same loop
  controlled loopHCCompleted: IntHCMgA -> Boolean

definitions:

  //Refined for sequencing different MAPE loops executions
  function startIntHCM($b in IntHCMgA) =
    loopHCCompleted($b)

  //Refined to check if adaptation is required
  function startMainHCA($b in MainHCMgA) =
   (heatingsON and (exist $a in fromMainHCMtoIntHCM($b)
      with neq(desiredHeatingSetting($a),computeHeatingSetting($a)))) or
   (heatingsON and (exist $c in fromMainHCMtoIntHCM($b)
      with eq(windowsStatusSaved($c),OPEN)) )

  ...

  //Added in refinement to compute the desired heating setting
  function computeHeatingSetting($a in IntHCMgA) =
    let ($t = temperatureSaved($a)) in
      if $t < temperature_MidpointSaved($a) then //e.g. < 10
        VERY_HOT
      else
        if $t < temperature_SetpointSaved($a) then //e.g. < 18
          FAIRLY_HOT
        else
          STOPPED
        endif
      endif
    endlet

  //Added in refinement
  function heatingsON = (exist $a in IntHCMgA with heatingStatusSaved($a) = ON)

  //Added in refinement. It saves the temperature−related data of a room/zone (sensed by
  //the managed thermostat) and windows status into the knowledge
  rule r_SaveSensorsData =
    par
      temperatureSaved(self) := temperature(heatingManagedByIntHC(self))
      temperature_SetpointSaved(self) := temperature_Setpoint(heatingManagedByIntHC(self))
      temperature_MidpointSaved(self) := temperature_Midpoint(heatingManagedByIntHC(self))
      windowsStatusSaved(self) := windowsStatus(airManagedByIntHC(self))
      heatingStatusSaved(self) := heatingStatus(heatingManagedByIntHC(self))
    endpar
```

```
  //** Interface group MAPE components' behavior **
  rule r_CleanUp_IntHCM =
    loopHCCompleted(self) := false //added in refinement

  rule r_IntHCM =
    if startIntHCM(self) then
      par
        r_SaveSensorsData[] //added in refinement
        if not sgnIntHCMMainHCM(self,fromIntHCMtoMainHCM(self)) then
          sgnIntHCMMainHCM(self,fromIntHCMtoMainHCM(self)) := true endif
        r_CleanUp_IntHCM[]
      endpar
    endif

  rule r_CleanUp_IntHCE =
    par
      sgnMainHCEIntHCE(fromIntHCEtoMainHCE(self), self) := false
      loopHCCompleted(self) := true //added in refinement
    endpar

  rule r_IntHCE =
    if startIntHCE(self) then
      par //Added in refinement: final setting for the actuators
        heating_Setting(heatingManagedByIntHC(self)):= desiredHeatingSetting(self)
        windows_Setting(airManagedByIntHC(self)):= desiredWindowsStatus(self)
        r_CleanUp_IntHCE[]
      endpar
    endif

  //** Main group MAPE components' behavior **
  rule r_MainHCM =
    if startMainHCM(self) then
      par
        r_MainHCA[]
        r_CleanUp_MainHCM[]
      endpar
    endif

  rule r_CleanUp_MainHCA =
  //if no adaptation was necessary, cleaning of loop completion flags is done here
    forall $a in fromMainHCMtoIntHCM(self) with loopHCCompleted($a) = false do
        loopHCCompleted($a) := true

  //Refined
  rule r_MainHCA =
    if startMainHCA(self) then
        r_MainHCP[]
    else r_CleanUp_MainHCA[] endif

  //Refined
  rule r_MainHCP =
    if startMainHCP(self) then
      par
        forall $a in fromMainHCMtoIntHCM(self) do
          par
            desiredHeatingSetting($a) := computeHeatingSetting($a)
            if (heatingsON and windowsStatusSaved($a) = OPEN) then
              desiredWindowsStatus($a) := CLOSED endif
          endpar
        r_MainHCE[]
      endpar
    endif

  rule r_MainHCE =
    if startMainHCE(self) then
      forall $a in fromMainHCMtoIntHCM(self) do
          sgnMainHCEIntHCE(self, $a) := true
    endif

...
default init s0:
  ...
  //Added in refinement
  function desiredHeatingSetting($a in IntHCMgA) = STOPPED
  function loopHCCompleted ($a in IntHCMgA) = true
```

Code 10: Excerpt of the refined ASM model of the Heating Comfort (HC) MAPE loop

tionality to keep windows closed when heating is on.

Moreover, a flag (the boolean-valued function `loopHCCompleted`) has been added for the coordination of different execution instances of the compound MAPE loop; here we assume that different executions of the same compound loop are done one at a time to avoid to handle another adaptation cycle while one is still executing and the loop knowledge is in a transient state.

Then, some derived boolean-valued functions generated and used as guards for triggering the MAPE rules (components) have been refined. For example, the function `startIntHCM` for triggering the component M of an interface group has been defined to be exactly the logical boolean-valued function `loopHCCompleted` in order to start a new execution of the loop only when the previous one (if any) completed.

Finally, placeholders of component rules and

cleaning rules have been refined. For example, in `r_IntHCE`, the final setting for heating and windows, respectively, is done by updating the functions `heating_Setting` and `windows_Setting` according to the planned decisions.

7.2. Simulation-based analysis

The first kind of analysis that a designer can perform is model validation by simulation. Through simulation, the developer can interact with the model and get an early understanding of its behavior; already at this stage, trivial errors can be discovered. The ASMETA framework provides three ways of simulating the model:

1) interactive textual simulation by the AsmetaS tool [19] in which the user interactively sets the values of monitored functions and inspects the simulation output for checking correctness;
2) graphical animation by the AsmetaA tool [20] that provides a visualization of the output of the AsmetaS simulator. The tool facilitates the understanding of the simulation, as it provides a more compact visualization of the states and shows which locations have changed between two consecutive states and which have been remain unchanged;
3) scenario-based simulation by the AsmetaV [21] tool in which the user specifies in a *scenario* (similar to a test case) the interaction with the model: (s)he can set values for monitored functions, enforce a simulation step, and check that some predicates hold in some given states.

As example of model validation, we here use the animator AsmetaA. Fig. 6 shows a simulation trace in which the user sets, in the initial state, the status of the house: at each floor the heater is turned on (`heatingStatus(hs_gf)` and `heatingStatus(hs_ff)`), at least one window is open on ground floor (`windowsStatus(hs_gf)`), all windows are closed on first floor (`windowsStatus(hs_ff)`), and the temperature on both floors is 18 (`temperature(hs_gf)` and `temperature(hs_ff)`) with a desired temperature of 20 (`temperature_Setpoint(hs_gf)` and `temperature_Setpoint(hs_ff)`). Starting from this setting, the MAPE loop for HC concern decides to perform adaptation and, in three steps, it closes the window at the ground floor (`windowsSetting(hs_gf)`) and sets the heating system to FAIRLY_HOT on both floors (`heatingSetting(hs_gf)` and `heatingSetting(hs_ff)`). In the online repository, we also report an AsmetaV scenario automatizing this simulation trace.

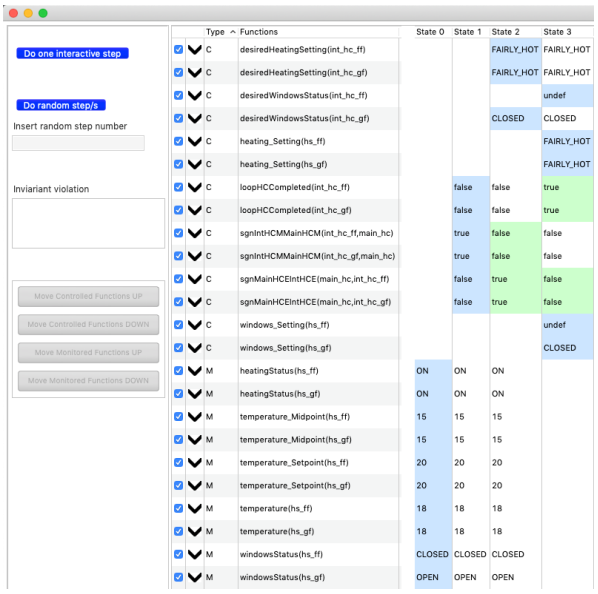


Figure 6: Simulation through the AsmetaA tool

7.3. Model checking-based analysis

Although simulation is very useful and it often allows to quickly find trivial model faults, more subtle faults may be more difficult to discover and, therefore, more advanced analysis techniques exploring the whole state space need to be applied.

As first technique, the designer can specify application-dependant temporal properties (either CTL or LTL) over the model and check them using the AsmetaSMV model checker [22]. For example, for the HC concern of the running case study, we specified the following properties regarding the adaption correctness:

$$\mathbf{G}((\text{heatingsON and temperatureSaved(int\_hc\_gf)} < \text{temperature\_MidpointSaved(int\_hc\_gf)}) \text{ implies } \mathbf{F}(\text{heating\_Setting(hs\_gf)} = \text{VERY\_HOT}))$$
$$\mathbf{G}((\text{heatingsON and temperatureSaved(int\_hc\_ff)} < \text{temperature\_MidpointSaved(int\_hc\_ff)}) \text{ implies } \mathbf{F}(\text{heating\_Setting(hs\_ff)} = \text{VERY\_HOT}))$$
$$\mathbf{G}((\text{heatingsON and windowsStatusSaved(int\_hc\_gf)} = \text{OPEN}) \text{ implies } \mathbf{F}(\text{windows\_Setting(hs\_gf)} = \text{CLOSED}))$$
$$\mathbf{G}((\text{heatingsON and windowsStatusSaved(int\_hc\_ff)} = \text{OPEN}) \text{ implies } \mathbf{F}(\text{windows\_Setting(hs\_ff)} = \text{CLOSED}))$$

The first two properties check that, whenever the saved temperature value is below the desired value in a given floor, the heating system will be eventually set to the maximum power (i.e., VERY_HOT). The last two properties, instead, check that if, in

a given floor, at least one window is open and the heating system is turned on, the windows will be eventually closed. Similar application-dependant properties have been specified for the other two adaptation concerns and can be found in the online repository.

The tool AsmetaMA [23] of the ASMETA framework, instead, allows to check application-independent properties that any model should guarantee (called *meta-properties*). The tool checks 7 meta-properties related to *minimality*, *completeness*, and *consistency*. For example, the consistency meta-property MP1 checks that there are no *inconsistent updates* [8], i.e., no location is updated to two different values at the same time. We applied the model reviewer to all the models developed for the running case study and it proved to be useful on the model combining the AQ and HC concerns; indeed, for this model, AsmetaMA found that MP1 is violated as location `windows_Setting(aqs_gf)` (similarly, also location `windows_Setting(aqs_ff)`) can be updated simultaneously to OPEN and CLOSED when the MAPE loop for AQ tries to open the window to refresh the air, and the MAPE loop for HC tries to close it to avoid that the windows are open when the heating system is on. Thanks to this analysis result, we realized that the original MSL design was not accurate enough and it was not implementing a proper coordination schema between the MAPE loops handling the conflicting concerns; this lead us to redesign the MSL model as explained in the next section.

8. Analysis-driven re-design of the smart home case study

To resolve the conflict arising between the goals of the MAPE loops for AQ and HC concerns in managing the windows opening/closure, the MAPE loops need to cooperate and coordinate actions to avoid interferences and provide certain guarantees about adaptations. To this purpose, the two MAPE loops have been composed to realize a control hierarchy according to the abstract pattern definition already presented in Code 4, Sect. 4. Code 11 shows the corresponding concrete pattern and its instance for the compound concern AQ_HC. A higher MAPE group `high_aq_hc` operates at a longer time scale with a more global/strategic vision and may prioritize actions of the loops `main_aq` for AQ and `main_hc` for HC at lower layers that operate at a short time scale, guaranteeing timely adaptation concerning the part of the system under their direct control. The possibility of interference between the two loops is now made explicit at MSL model level (see Code 11) by specifying the air (windows) sub-

```
import HierarchicalControlMAPE
concrete pattern Hierarchical_AQ_HC_MAPE
        concretizationOf HierarchicalControlMAPE {
  //Heating sub−system
  system SysH: HierarchicalControlMAPE.SysOne
  //Air (windows) sub−system
  system SysA: HierarchicalControlMAPE.SysTwo

  group MainHC: HierarchicalControlMAPE.Intermediate
  group IntHC: HierarchicalControlMAPE.InterfaceOne
  group MainAQ: HierarchicalControlMAPE.InterfaceTwo
  group HighAQ_HC: HierarchicalControlMAPE.High
}

configuration MySmartHomeAQ_HC instanceOf
                              Hierarchical_AQ_HC_MAPE {
  hs_ff: Hierarchical_AQ_HC_MAPE.SysH //heating Fst Floor
  hs_gf: Hierarchical_AQ_HC_MAPE.SysH //heating Gr Floor
  aqs_gf: Hierarchical_AQ_HC_MAPE.SysA //air Gr Floor
  aqs_ff: Hierarchical_AQ_HC_MAPE.SysA //air Fst Floor

  //group for the concern Air Quality
  main_aq: Hierarchical_AQ_HC_MAPE.MainAQ {
    managedSyS aqs_gf, aqs_ff
    components m_aq:M, a_aq:A, p_aq:P, e_aq:E
  }

  //main group for the concern Heating Comfort
  main_hc: Hierarchical_AQ_HC_MAPE.MainHC {
    components m_hc:M, a_hc:A, p_hc:P, e_hc:E
  }

  //interface group for the ground floor heating and windows
  int_hc_gf: Hierarchical_AQ_HC_MAPE.IntHC {
    managedSyS hs_gf, aqs_gf
    components m_hc:M, e_hc:E
  }

  //interface group for the first floor heating and windows
  int_hc_ff: Hierarchical_AQ_HC_MAPE.IntHC {
    managedSyS hs_ff, aqs_ff
    components m_hc:M, e_hc:E
  }

  //higher group
  high_aq_hc: Hierarchical_AQ_HC_MAPE.HighAQ_HC {
    managedGrp main_hc, main_aq
    components m_h:M, a_h:A, p_h:P, e_h:E
  }

  //interactions
  main_aq.m_aq −> main_aq.a_aq
  main_aq.a_aq −> main_aq.p_aq
  main_aq.p_aq −> main_aq.e_aq
  main_hc.m_hc −> main_hc.a_hc
  main_hc.a_hc −> main_hc.p_hc
  main_hc.p_hc −> main_hc.e_hc
  int_hc_gf.m_hc −> main_hc.m_hc
  int_hc_ff.m_hc −> main_hc.m_hc
  main_hc.e_hc −> int_hc_gf.e_hc
  main_hc.e_hc −> int_hc_ff.e_hc
  high_aq_hc.a_h −> high_aq_hc.e_h
}
```

Code 11: MAPE loop for the concern AQ_HC

```
rule r_HighAQ_HCE =
    if startHighAQ_HCE(self) then
      par
        if (isDef(desiredWindowsStatus(main_aq))) then
            desiredWindowsStatus(self):= desiredWindowsStatus(main_aq)
        else desiredWindowsStatus(self):= undef endif
        if (not(sgnHightoMainHC_E(main_hc))) then sgnHightoMainHC_E(main_hc):= true endif
        if (not(sgnHightoMainAQ_E(main_aq))) then sgnHightoMainAQ_E(main_aq):= true endif
        r_CleanUp_HighAQ_HCE[]
      endpar
    endif
```

Code 12: Excerpt of the ASM model of the AQ_HC MAPE loop

systems (`aqs_gf` and `aqs_ff`) of the two floors as managed subsystems of both the two loops for AQ and HC (`aqs_gf` is managed by groups `int_hc_gf` and `main_aq`, and `aqs_ff` is managed by groups `int_hc_ff` and `main_aq`).

Starting from the self-adaptive ASM generated from this new MSL model for AQ_HC, we reused part of the behavior specification for the MAPE components of the two loops AQ and HC and we further refined and extended it to capture the intended cooperation and coordination as realized by the new arbiter agent for the higher group. The complete ASM model for the compound concern AQ_HC is available online. Code 12 reports an excerpt of the component E (rule `r_HighAQ_HCE`) of the higher group showing how decision is made to resolve the conflict. It is just a way to solve it; essentially, if the location value `desiredWindowsStatus` has been established for AQ, discordant or not in value with that for HC, the last decision is made by the higher agent in favour of the desired setting of AQ, and communicated to the components E of the managed lower groups. The lower agents' components E (not shown in Code 12) will then consider the decision of the higher agent in actuation.

9. Tools implementation around MSL

Around the MSL language, as long-term plan, we are developing a pattern-oriented framework for the design of the managing layer in self-adaptive systems. The idea is to have a framework centered around MSL, and extensible by including external components for different activities around the models. The overall framework is depicted in Fig. 7.

The MSL editor, together with its parser and validator (presented in Sect. 4.3), makes up the modeling front-end. The Xtext/EMF approach MSL has been built on, facilitates the development of compilers (i.e., *model generators*) toward other (back-end) frameworks by using principles and tools of the model-driven engineering.

The model generator `MSL2ASM`, for example, automatically translates MSL models into self-adaptive ASMs. It has permitted the integration of the ASMETA toolset into the MSL-centric framework as back-end for formal validation and verification of the MSL models (some of the ASMETA features have been presented in Sect. 7). `MSL2ASM` has been developed in Java using a Model-to-Text (M2T) approach. According to the mapping rules synthesized in Table 3, the generator visits the MSL ecore metamodel instance – i.e., the abstract syntax tree (AST) of an MSL model[14] – to produce the corresponding ASM model. The generator can be installed as eclipse plugin together with the MSL editor.

Recently, another component has been integrated into the framework as implementation back-end of MSL models in the context of the smart home systems. A model generator `MSL2OpenHAB` has been implemented by using the same M2T approach and automatically translates MSL models into a set of OpenHab items and a set of *Event-Condition-Actions* rules of the OpenHAB automation rule engine. A preliminary version of this component, whose presentation is out of the scope of this paper, has been presented in [24]. This component allows the use of OpenHAB both as platform to implement the managed layer of a self-adaptive system (as used in this paper) and to implement the managing layer.

10. Assessment of the MSL modeling language

In this section, we discuss about the assessment of the MSL language concerning its support for the requirements presented in Sect. 4.1. We discuss them individually, specifying also a degree of support (low, medium, and high).

Model purpose. (High support). To achieve the model purpose expressed for MSL and the vision of an MSL-centric modeling framework, we adopted a loose-form of modeling/coding language composition via sharing a set of core concepts/abstractions with the same semantics. Tools that ma-

[14] This AST is the EMF ecore model of MSL used as the in-memory objects representation of any parsed MSL text file.

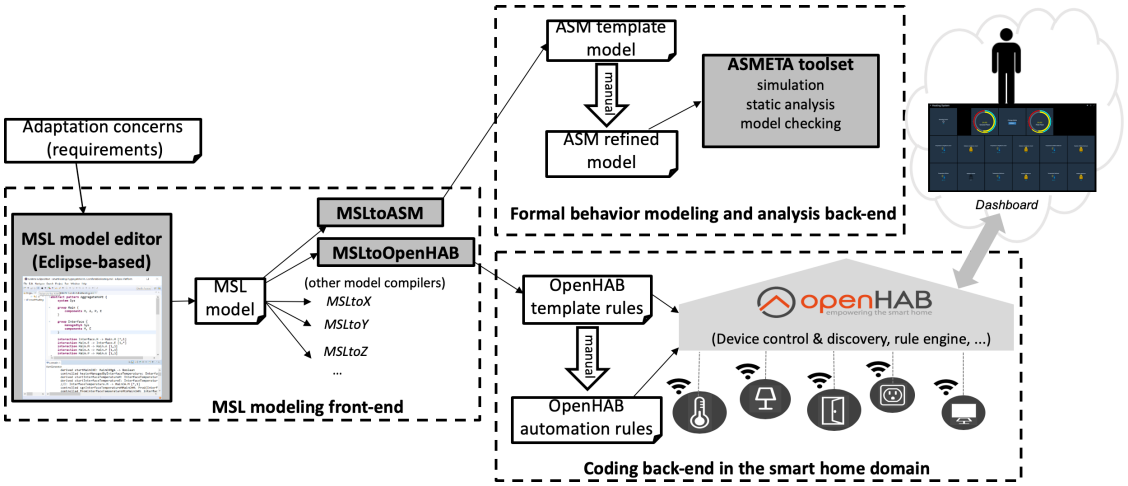


Figure 7: Overview of the MSL-centric framework

nipulate models/code do not exchange information explicitly, but reason about artifacts related to shared semantic concepts/abstractions [25]. The MSL framework realizes this loose-form of language composition based on a *core* DSL of the *model space* (i.e., MSL) and on *implicit modeling* [26] in the DSLs of the target *solution spaces* (such as the ASM-based ASMETA formal analysis toolset). Essentially, we employ ground MSL models for the structuring of the adaptation loops activities as composable units w.r.t. the adaptation concerns; we implicitly model the loops structure via model/code generators towards specific solution spaces; and via incremental refinement in the target solution space, we complete the behavioral specification of the loops activities in an operational form.

The ASM-based ASMETA specification and analysis toolset was the first back-end module introduced in the MSL framework to enable formal specification of MAPE-K loops behavior (the internal MAPE components behavior) and its formal analysis (validation and verification).

A second back-end module was recently introduced [24] for the generation of implementation code in the rule-based programming environment of the smart home platform OpenHAB. Due to the fact that the two back-end modules are quite diverse (syntactically and semantically), we think that the degree of support is high. However, to completely assess the level of fulfilment of such a requirement, more translation toward other back-end frameworks are needed.

Separation of concerns (High support). According to such a best practice, in MSL we support separation of adaptation concerns and the design of their MAPE-K loop models separately as instances of specific MAPE patterns.

Principle of Least Knowledge. (High support). A single or structured MAPE-K loop inherently satisfies such a principle, since MAPE-K components interact according to a pre-fixed sequence of interactions and communicate data via a shared knowledge. So MAPE components do not depend on the internal structure of other MAPE components, and therefore they can be replaced without impact on the others.

Minimize upfront design. (Medium support). Thanks to the support of the separation of adaptation concerns and to the definition of a separate (possibly structured) MAPE-K loop for each of them, MSL provides a way to create just enough upfront design that does not become a burden for designers. Though we do not mention here any development methodology for self-adaptive systems explicitly, we believe that, since MSL allows the creation of a minimal initial design of the MAPE-K loops structure, MSL thus provides only required details as needed to support the analysis and design in agile iterations.

Pattern-oriented design. (High support). MSL fully supports the pattern-oriented approach proposed in [5] to the design of the adaptation layer in terms of recurring structures of MAPE-K loops. Design experts can use MSL built-in patterns but

also add, extend, and modify patterns to tailor them to their own needs. MSL allows both the description and concrete use of the decentralized MAPE patterns given in [5], and also the definition of new ones just as they are borne from experience or as result from a pattern composition.

Model composability. (Medium support). Currently, we support MSL model composition at the level of the definition of the abstract patterns, essentially by integrating the definition of their corresponding abstract patterns into one abstract pattern. An example of such composition was presented in Sect. 8 where we introduced a new pattern to compose two existing MAPE loops in a control hierarchy. As future work, we intend to extend the MSL language with patterns composition operators applicable during the concretization phase of a pattern instantiation.

Concerning the problem of assuring the dependability and trustworthiness after the composition, thanks to the model projection into the ASM-based ASMETA space, we are able to provide assurance on the functional correctness of the MAPE-K loop behavior as resulting from the composition. Assurance of quality properties of the adaptation layer itself is not yet supported by the MSL framework, but recently we have been investigating on how to support it by introducing the notion of *self-accounting* as self-* property and presenting an inductive method that, based on the structure of the MAPE patterns, evaluates the cost of the adaptation logic (in terms, for example, of latency time and availability) [27].

11. Threats to validity

Following the approach outlined in [28, 29] we discuss potential threats to the validity of the proposed language and approach.

To smooth the *construct validity* threat, we have designed the whole language following proven principle in software engineering as, the separation of concerns, the pattern oriented design, and the model composability (see Sect. 4.1). The fulfillment of these principles is thoroughly discussed in Sect. 10.

A threat to *internal validity* is that the ASM generator `MSL2ASM` could be not correct and, therefore, the produced ASMs would not be self-adaptive ASMs that correctly describe the MAPE patterns of the corresponding MSL models. To deal with this threat, we check that the produced ASM models are indeed correct by applying the "MAPE-K Correctness Verification" approach described in [9]. The approach generates a set of LTL properties starting from an ASM model A that allegedly implements a self-adaptive ASM; each property is the LTL characterization of an indirect interaction $X \rightarrow Y$ of the MAPE loop that should be implemented: intuitively, it states that if Y occurs, X occurred in the past and triggered Y. If all the generated LTL properties are verified, the ASM A is indeed a self-adaptive ASM. We applied this technique to all the generated ASMs[15] and it confirmed that they are self-adaptive ASMs. Although this is not a proof of total correctness, it provides a good degree of confidence that the generator `MSL2ASM` is correct.

A threat to *external validity* is the representativeness of the case study. In fact, as discussed above, MSL has been assessed through the development of a smart home case study, therefore only a limited set of features has been investigated. To smooth this threat, we have applied MSL to another case study from the automotive domain. In particular, we modeled the adaptive features (the adaptive high beam headlights and the adaptive cruise control) of the *Adaptive Exterior Light and Speed Control Systems*[16]. Further details are publicly available[17]. Another possible threat to external validity is the usability of the language. To smooth this threat, the syntax of the proposed language is intuitive and self-explanatory. We have also performed an initial qualitative evaluation with a small set of colleagues obtaining a positive feedback. As a future work, we plan to include external experts (students and professionals) in a controlled experiment which will design a fully-featured application in the context of an ongoing research project. Hence, a quantitative evaluation of the experience in adopting MSL can be performed to derive some meaningful statistics about the language usability.

Regarding the *reliability validity* threat, researchers willing to adopt MSL to model their managing systems in accordance to the patterns in [5] are supported by the fact that the existing MAPE patterns are now pre-defined and publicly available

[15] Models used for validation of `MSL2ASM` are reported in `https://github.com/fmselab/msl/tree/master/org.xtext.msl.asmgenerator/modelsForValidation`

[16] `https://abz2020.uni-ulm.de/case-study`

[17] `https://github.com/fmselab/msl/tree/master/examples/CarSystem`

in MSL. Besides, the language itself has been conceived at a fine granularity level that allows an easy definition of new patterns that can extend the pattern library. Moreover, to provide graphical views of MSL models (similarly to those in [5]), we are in the process of implementing also a graphical visualizer.

12. Related work

We give here a brief overview of selected works that are related to notations and tools for explicitly modeling MAPE loops (and patterns) that we identified as the most relevant to the context of this work.

Languages. Contributions in [30, 31] exploit the use of a network of Timed Automata to specify the behavior of MAPE components, and the Uppaal model checker for property verification. A development methodology, called ENTRUST, supports the systematic engineering and assurance of self-adaptive systems. In ENTRUST, a template-based approach to the design and verification of a "specific family" of self-adaptive systems is used, namely a target domain of distributed applications in which self-adaptation is used for managing resources for robustness and openness requirements via adding/removing resources from the system. In [32], a UML profile is proposed to model control loops as first-class entities when architecting software with UML. The UML profile supports modeling of interactions between coarse-grained controllers, while the MSL language aims at modeling finer-grained interactions between the MAPE components. A dedicated model language, called Stitch, has been presented in [33], to support adaptation strategies in self-adapting software architectures. The language, used in the Rainbow framework [34], defines adaptation strategies as decision trees and allows the explicit representation of quality of services objectives, the selection of strategies that optimize the system utility considering also the presence of potential timing delays and outcome uncertainty.

With respect to these languages, that do not explicitly model MAPE loops, in MSL, we elevate them to first-class entities for structuring the adaptation logic of any self-adaptive system in the early design phases and for fostering (in a broad sense) *pattern-oriented modeling*.

Tools. SOTA (State Of The Affairs) [35], supported by the Eclipse plug-in SimSOTA, is a goal-oriented approach for modeling, simulating and validating self-adaptive systems. Unlike our approach, SOTA adopts a semi-formal notation, namely UML activity diagrams, to model the behavior of feedback loops. The framework ACTRESS [36] is grounded on an actor-oriented component metamodel and provides support for structural modeling of feedback loops, model well-formedness checking (through structural OCL or Xbase invariants), and generation of Java-like code for the actor- and JVM- based runtime platform Akka. Both SOTA and ACTRESS do not support pattern modeling and do not adopt a formal notation, as self-adaptive ASMs, for the behavior specification and verification of MAPE components.

ActivFORMS (Active FORmal Models for Self-adaptation) [37] is a virtual machine to realize self-adaptation with guarantee. Timed automata are used to design the MAPE-K loops accomplishing given adaptation goals. These models are verified off-line and at run-time, and can be updated on the fly to support changing goals. ActivFORMS shares with us a formal description of the adaptation for verification, but it does not support coding of the models. CYPHEF (CYber-PHysical dEvelopment Framework) [38] provides a graphical notation for modeling the control architecture of a cyber-physical system by MAPE loop patterns. Differently from our approach, CYPHEF does not provide support for the specification and formal verification of the MAPE components' behavior.

Despite similarities and differences with our approach, all the works mentioned above can be used as back-end frameworks to complement and complete for different purposes the adaptation logic design started in MSL.

13. Conclusion and future work

We proposed the textual language MSL for defining and instantiating MAPE patterns in structuring the adaptation logic of self-adaptive systems. The language provides a textual counterpart of the graphical notation originally presented in [5] for specifying MAPE patterns, but never developed and exposing a number of ambiguities. A semantic mapping and a model generator from MSL to self-adaptive ASMs has been also presented. It provides a connection to the modeling back-end of ASMs for specifying and analysing the behavior of instances of MAPE patterns formally. The language has been

used to model the adaptation layer of case studies in the area of smart home and vehicle automation.

MSL can be used to model complex composite MAPE loops structures. We support a repository where all patterns devised in [5] are available, and we have shown how to define new patterns in MSL. As future work, we intend to extend the MSL pattern library with other common patterns of interacting MAPE loops, and the language itself to allow composition strategies of patterns instances in the same design.

Another direction that we intend to pursue is the evaluation of the usability and usefulness of the framework on a certain number of case studies, and to evaluate mapping towards other back-end frameworks to improve MSL features. Finally, we also plan to extend our framework in order to support an automatic backward compatibility between an MSL model and its ASM counterpart.

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