

# PobSAM: Policy-based Managing of Actors in Self-Adaptive Systems

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## Abstract

In this paper, we present a formal model, named PobSAM (Policy-based Self-Adaptive Model), for modeling self-adaptive systems. In this model, policies are used as a mechanism to direct and adapt the behavior of self-adaptive systems. A PobSAM model consists of a set of self-managed modules (SMM). An SMM is a collection of autonomous managers and managed actors. Managed actors are dedicated to functional behavior while autonomous managers govern the behavior of managed actors by enforcing suitable policies. To adapt SMM behavior in response to changes, policies governing an SMM are adjusted, i.e., dynamic policies are used to govern and adapt system behavior. We employ the combination of an algebraic formalism and an actor-based model to specify this model formally. Managers are modeled as meta-actors whose policies are described using an algebra. Managed actors are expressed by an actor model. Furthermore, we provide an operational semantics for PobSAM described using labeled transition systems.

*Keywords:* Adaptive systems, Policy-based Computing, Component-based Design, Algebra, Actor Models

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# 1 Introduction

**Motivation** Increasingly, software systems are subjected to adaptation at run-time due to changes in the operational environments and user requirements. Adaptation is classified into two broad categories [1]: structural adaptation and behavioral adaptation. While structural adaptation aims to adapt system behavior by changing system’s architecture, the behavioral adaptation focuses on modifying the functionalities of the computational entities.

There are several challenges in developing self-adaptive systems. Due to the fact that self-adaptive systems are often complex systems with greater degree of autonomy, it is more difficult to ensure that a self-adaptive system behaves as intended and avoids undesirable behavior. Hence, one of the main concerns in developing self-adaptive systems is providing mechanisms to trust whether the system is operating correctly, where *formal methods* can play a key role.

Zhang et al. [2] proposed a model-driven approach using Petri Nets for developing adaptive systems. They also presented a model-checking approach for verification of adaptive system [3,4] in which an extension of LTL with "adapt" operator was used to specify the adaptation requirements. In this work, system was modeled using a labeled transition system. Furthermore, authors in [5,6] used labeled transition systems at a low level of abstraction to model and verify embedded adaptive systems. Kulkarni et al. [7] proposed a theorem proving approach to verify the structural adaptation of adaptive systems.

*Flexibility* is another main concern to achieve adaptation. Since, hard-coded mechanisms make tuning and adapting of long-run systems complicated, so we need methods for developing adaptive systems that provide a high degree of flexibility. All the proposed formal models hard-code the adaptation logic which leads to system’s inflexibility. Recently, the use of policies has been given attention as a rich mechanism to achieve flexibility in adaptive system. A policy is a rule describing under which condition a specified subject must (can or cannot) do an action on a specific object. In [8,9,10,11,24], policies are used as a structural adaptation mechanism. Additionally, [12,13] proposed architectures for engineering autonomic computing systems that use policies for behavioral adaptations.

**This paper** In this paper we propose a formal model called PobSAM (Policy-based Self-Addaptive Model) for developing and specifying self-adaptive systems that employs policies as the principal paradigm to govern and adapt system behavior. We model a self-adaptive system as a collection of interacting actors directed to achieve particular goals according to the predefined policies. A PobSAM model consists of a set of Self-Managed Modules(SMMs). An SMM is composed of a collection of autonomous managers and managed actors. Autonomous managers are meta-actors responsible for monitoring and handling events by enforcing suitable policies. Each manager adapts its policies dynamically in response to the changing circumstances according to adaptation policies. The behavior of managed actors is governed by managers, and cannot be directly controlled from outside.

PobSAM has a formal foundation that employs an integration of algebraic formalisms and Actor-based models. The computational (functional) model of PobSAM is based on actor-based models while an algebraic approach is proposed to

specify policies of managers. Operational semantics of PobSAM is described with labeled transition systems. The proposed model is suitable for cases where the set of governing policies of each context is known in advance.

In our previous work [14], we proposed a formal model for policy-based self-adaptive systems using an actor-based language Rebeca [15]. In [14], we added policies as rules to the Rebeca code and we focused on policy conflict detection. Combining adaptation concerns with system functionality in [14] increases the complexity of the model as well as the formal verification process. In order to address these drawbacks, we need an approach in which adaptation concerns are separated from system functionality. Here, we extracted the policy rules, specified by an algebraic formalism, from Rebeca code. Moreover, the policies are presented in two classes, separating the policies governing the actor behavior from the policies which determine the adaptation strategy (when and how the system passes the adaptation phase safely). Additionally, here we added modules as an encapsulation mechanism in which each module can manage itself autonomously.

**Contribution** Formal methods are proposed for the analysis of adaptive systems, mainly at the low levels of abstraction, and flexible policy-based approaches are proposed for designing adaptive systems without formal foundation. Here, we propose a flexible policy-based approach with formal foundation to support modeling and verification of self-adaptive systems. Policies allow us to separate the rules that govern the behavioral choices of a system from the system functionality giving us a higher level of abstraction; so, we can change system behavior without changing the code or functionality of the system. We are also concerned about the adaptation strategy, to pass the adaptation phase safely and at the right moment. As an example, we are able to change and reason about the scheduling of jobs using policies independent of the system code. Although our approach can support both structural and behavioral adaptation, in this paper, we focus on the behavioral adaptation. The formal foundation, the modular model, and separation of adaptation rules will help us in developing rigorous analysis techniques.

**Structure of the paper** This paper is organized as follows. In Section 2 we introduce an example to illustrate our approach. Section 3 introduces the PobSAM model in brief. Sections 4 and 5 introduce the syntax and semantics of PobSAM respectively. Section 6 presents related work and compares our approach with the existing approaches. In Section 7, we present our conclusions and plans for the future work.

## 2 Smart Home

In a home automation system, sensors are devices that provide smart home with the physical properties of the environment by sensing the environment. In addition, actuators are physical devices that can change the state of the world in response to the sensed data by sensors. The system processes the data gathered by the sensors, then it activates the actuators to alter the user environment according to the predefined set of policies. Smart homes can have different features. Here, we take into account three features including: (1) The lighting control which allows lights to switch on/off automatically depending on several factors. In addition, the intensity

of the lights placed in a room can be adjusted according to the predefined policies. (2) Doors/Windows management that enable inhabitants to manage windows and doors automatically. In addition, if windows have blinds, these should be rolled up and down automatically too. (3) Heating control which allows inhabitants to adjust the heating of the house to their preferred value. The heating control will adjust itself automatically in order to save energy.

The smart home system is required to adapt its behavior according to the changes of the environment. To this aim, we suppose that the system runs in normal, vacation and fire modes and in each context it enforces various sets of policies to adapt to the current conditions. For the reason of space, here we only identify policies defined for lighting control module while the system runs in normal and fire modes as follows:

#### Defined policies in the normal mode

- P1** Turn on the lights automatically when night begins.
- P2** Whenever someone enters an empty room, the light setting must be set to default.
- P3** When the room is reoccupied within T1 minutes after the last person has left the room, the last chosen light setting has to be reestablished.
- P4** The system must turn the lights off, when the room is unoccupied.

#### Defined policies in the fire mode

- P1** Turn on the emergency light.
- P2** Disconnect power outlets.
- P3** When the fire is extinguished, turn off the emergency light.

### 3 Modeling Concepts of PobsSAM

Self-Managed Module (SMM) is the policy-based building block of PobsSAM. A PobsSAM is composed of a set of SMMs. An SMM, in turn, may contain a number of SMMs structured hierarchically. An SMM is a set of actors which can manage their behavior autonomously according to predefined policies. PobsSAM supports interactions of an SMM with the other SMMs in the model. To this aim, each SMM provides well-defined interfaces for interaction with other SMMs. In the smart home case study, we consider three SMMs including *LightCIModule*, *TempCIModule* and *DWCIModule* to manage lighting, temperature and doors/windows respectively.

An SMM structure can be conceptualized as the composition of three layers illustrated in Figure 1.

- **Managed Actors Layer** This layer is dedicated to the functional behavior of SMM and contains computational actors. Actors are governed by autonomous managers using policies to achieve predefined goals. Henceforth, we use the terms managed actors and actors interchangeably.
- **Autonomous Managers Layer** Autonomous managers are meta-actors that can operate in different configurations. Each configuration consists of two classes of policies: governing policies, and adaptation policies. Using governing policies,

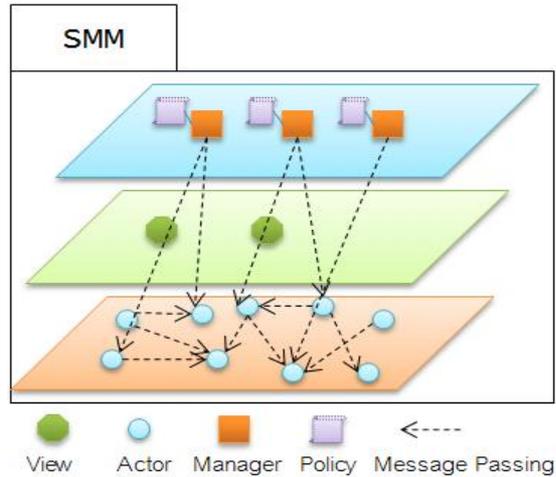


Fig. 1. The PobsSAM Model

the manager directs the behavior of actors by sending messages to them. Adaptation policies are used to switch between different configurations to adapt the module behavior properly. Moreover, a manager may have its local variables too.

- **View Layer** In PobsSAM, each actor provides its required state information to the relevant managers. Not all aspects of the operational environment have direct influence on the behavior of managers, the views provide only the required information for managers. The view layer is composed of views that provide a view or an abstraction of an actor's state that is adequate for the managers' needs. The distinction between the underlying computational environment and the required state information of actors makes analyzing managers much simpler.

**Example 3.1** In our example, *LightClModule* module comprises an autonomous manager named *LightMngr*, two *light* actors (*light1* and *light2*), an outlet actor and a number of views indicating the overall light intensity of room and the status of the lights.

## 4 PobsSAM Syntax

Figure 2 shows a typical SMM containing manager meta-actors, views and actors, which we elaborate in the sequel.

### 4.1 Actors

The encapsulation of state and computation, and the asynchronous communication make actors a natural way to model distributed systems. Therefore, we use an actor-based model to specify the computational environment of a self-adaptive system. To this aim, an extension of Rebeca is used. Rebeca [15] is an actor-based language for modeling concurrent asynchronous systems which allows us to model the system as a set of reactive objects called rebecs interacting by message passing. Each rebec provides methods called message servers (msgsrv) which can be invoked by others. Each rebec has an unbounded buffer for coming messages, called queue.

```

SMM SMM1
Managers
  Manager ManagerName1(InitialConfiguration1)
    // definition of local variables
    Datatype var1;
    // manager's view
    <ViewName11,..., ViewName1n>;
    // definition of manager's configurations in terms of
    // their governing and adaptaion policies
    Configurations
      ConfigurationName1={gp11,...,gp1m}<ap11|...|ap1n>;
      .
      .
    EndC
  Policies
    //Definition of governing policies(gps)
    GoverningPolicyName1: on eventi if condi do actionsi;
    .
    .
    //Definition of adaptation policies(aps)
    AdaptationPolicyName1:
      on eventj if condj switcho Configuration1 when condk priority 0j;
    .
    .
  EndP
EndM
// definition of other managers
EndMS
Views
  //definition of views
  Datatype1 ViewName1 as expr1;
  Datatype2 ViewName2 as expr2;
  .
  .
EndV
Actors
  //definition of actors
  reactiveclass Classname1() {
    Knownrebecs{}
    Statevars{ Public datatype v1;
               Private datatype v2;}
    msgsrv initial() {}
    msgsrv msgsrv1(){}
  }
  main {
    ...
    Classname1 rebec1(...):(...);
    ...
  }
EndA
EndSMM

```

Fig. 2. The Typical Syntax of a PobSAM Model

Furthermore, the rebecs' state variables (statevars) are responsible of capturing the rebec state. The known rebecs of a rebec (Knownrebecs) denotes the rebecs to which it can send messages. In our extension, an actor can expose a number of its state variables to the managers (Figure 2). The exposed state variables are used in the definition of views.

**Example 4.1** In the *LightCIModule* SMM, the managed layer comprises a set of *light* rebecs controlled by *LightMngr*. We consider a reactive class named *Light* to model the lights which contains *setIntensity*, *switchOn* and *switchOff* message servers as well as *intensity* and *status* state variables.

#### 4.2 Views

In PobSAM, the views are defined in terms of the public state variables of actors. A view variable could be an actual state variable, or a function or a predicate applied to

state variables. Views enable managers not to be concerned about internal behavior of actors and they provide an abstraction of actor's state to managers.

**Example 4.2** In the *LightClModule* SMM, the *LightMngr* does not require the exact values of the lights intensities and providing overall intensity as low, medium or high values is sufficient to decide. The overall intensity is defined based on the *intensity* statevar of the *light* rebecs as a view.

### 4.3 Managers

In our model, policies direct the system behavior, and adaptation is achieved by changing policies. A manager can be in various configurations enforcing different policy sets. As shown in Figure 2, a manager is defined in terms of its possible configurations, its view of the actor layer and its local variables.

#### Governing Policies

Whenever a manager receives an event, it identifies all the policies that are triggered by that event. For each of these policies, the policy condition is evaluated if one exists. If the condition evaluates to true, the action part of the triggered policy is requested to execute by instructing the relevant rebecs to perform actions through sending asynchronous messages. We express governing policies using a simple algebra as follows, in which P and Q indicate the policy sets:

$$P, Q \stackrel{\text{def}}{=} P \cup Q | P - Q | P \cap Q | \{p\} | \emptyset$$

$P \cap Q$  means that intersection of policy sets P and Q is used to direct actors. P-Q reduces policy set P by eliminating all the policies in the second set Q.  $P \cup Q$  represents the union of P and Q governing the actors simultaneously.  $\{p\}$  denotes a policy set with the simple policy p as its member.  $P \cap Q$  and  $P \cup Q$  are commutative and associative.

A simple action policy  $p=[o,\varepsilon,\psi,\alpha]$  consists of priority  $o$ , event  $\varepsilon$ , optional condition  $\psi$  and action  $\alpha$ . In PobjSAM, events are defined as the execution of a message server, sending a message to a rebe, creating new actor or holding a specific condition in the system. Actions can be composite or simple. A simple action is of the form  $r.\ell(v)$  which denotes message  $\ell(v)$  is sent to actor r. Composite actions are created by composing simple actions as follows:

$$\alpha, \beta \stackrel{\text{def}}{=} \alpha; \beta | \alpha \parallel \beta | \alpha + \beta | [\omega? \alpha : \beta] | r.\ell(v)$$

Thus a composite action can be the sequential ( $\alpha; \beta$ ) or parallel execution ( $\alpha \parallel \beta$ ) of actions  $\alpha$  and  $\beta$ . Also, an action can be chosen to execute non-deterministically(+). Term ( $[\omega? \alpha : \beta]$ ) represents that action  $\alpha$  is chosen to be executed if  $\omega$  holds, else  $\beta$  will be chosen. + and  $\parallel$  are commutative and associative.

**Example 4.3** The governing policies of the *lightMngr* in the normal configuration

are as follows, where *night*, *occpd*, *rccpd* and *unoccpd* denote events and *c1*, *c2*, *d1* and *d2* are arguments indicating the light intensity.

$$\begin{aligned} p_{n1} &\stackrel{\text{def}}{=} [1, \textit{night}, \textit{true}, \textit{light1.switchon}() \parallel \textit{light2.switchon}()] \\ p_{n2} &\stackrel{\text{def}}{=} [2, \textit{occpd}, \textit{true}, \textit{light1.setIntensity}(d1) \parallel \textit{light2.setIntensity}(d2)] \\ p_{n3} &\stackrel{\text{def}}{=} [3, \textit{rccpd}, \textit{true}, \textit{light1.setIntensity}(c1) \parallel \textit{light2.setIntensity}(c2)] \\ p_{n4} &\stackrel{\text{def}}{=} [4, \textit{unoccpd}, \textit{true}, \textit{light1.switchoff}() \parallel \textit{light2.switchoff}()] \end{aligned}$$

### Adaptation Policies

One of the main characteristics of a formal model to specify a self-adaptive system is considering adaptation semantics. To this end, we should deal with a number of issues such as "the time at which an adaptation is performed in the system", "the time at which the manager's policies are modified", "the time at which the enforcement of new policies begin after modifying policies" or "the ability to restricting the system behavior during adaptation".

Whenever an event requiring adaptation occurs, relevant managers in different SMMs are informed. However, the adaptation cannot be done immediately and when the system reaches a safe state, the managers switch to the new configuration. Therefore, we introduce a new mode of operation named adaptation mode in which a manager runs before switching to the next configuration. While the manager is in the adaptation mode, it is likely that events occur which need to be handled by managers. To handle these cases, we introduce two kinds of adaptations named loose adaptation and strict adaptation. Under loose adaptation a manager enforces old policies, while under strict adaptation all events will be ignored until the manager exits the adaptation mode and the system reaches a safe state. For example in our smart home example, when *LightMngr* is in the fire configuration and there is a request for the vacation mode, while fire has not been put out, it keeps enforcing policies of the fire configuration by switching to the loose adaptation mode. Also, when *LightMngr* is in the normal configuration, once fire is detected, it stops enforcing its current policies by switching to the strict adaptation mode.

A simple configuration  $C$  is defined as  $C \stackrel{\text{def}}{=} \langle P, A \rangle$  where  $P$  and  $A$  indicate the governing policy set and the adaptation policy of  $C$  respectively. Adaptation policies are defined using an algebraic language as follows:

$$A \stackrel{\text{def}}{=} [D]_{\delta, \gamma, \lambda, \vartheta} | A \oplus A$$

in which  $D$ ,  $\delta$ ,  $\gamma$ ,  $\lambda$  and  $\vartheta$ , respectively denote an arbitrary configuration, the conditions of triggering adaptation, the conditions of applying adaptation, adaptation type (loose or strict) and the priority of adaptation policy. The simple adaptation policy,  $[D]_{\delta, \gamma, \lambda, \vartheta}$ , specifies when the triggering condition  $\delta$  holds and there is no other adaptation policy with the higher priority, the manager evolves to the strict or loose adaptation modes based on the value of  $\lambda$ . When the condition of applying adaptation  $\gamma$  becomes true, it will perform adaptation. Adaptation policies of a manager is defined as the composition,  $\oplus$ , of the simple adaptation policies. Here, composition of two policies means that those policies are potentially to be triggered.

$\oplus$  is associative and commutative.  $D$  is defined as follows where  $\omega$  is an arbitrary condition:

$$D, D' \stackrel{\text{def}}{=} [\omega?D : D']|D\Box D'|C$$

Terms  $[\omega?D : D']$  and  $D\Box D'$  represent conditional and non-deterministic choices respectively. In conditional choice, configuration  $D$  is chosen if  $\omega$  holds, else  $D'$  will be chosen. Non-deterministic choice means that the choice between configuration  $D$  or  $D'$  is made non-deterministically. This operator is associative and commutative.

**Example 4.4** In our smart home example, there are three configurations including  $C_n, C_v$  and  $C_f$ . Formal specification of *lightMngr*'s configurations are as follows in which  $p_{mj}$  denotes policy  $j$  defined in mode  $C_m$ . *vacReq*, *fire*, *firePutout* and *comebackHome* are events while *isPutout*, *isCnfrmd* and *onVac* are *lightMngr*'s local variables. As an example, when the *lightMngr* is in the *fire* mode and there is a request for going on vacation, while fire has not been put out, it can not switch to the  $C_v$  configuration.

$$\begin{aligned} C_n &\stackrel{\text{def}}{=} \langle \{p_{n1}, p_{n2}, p_{n3}, p_{n4}\}, [C_f]_{\text{fire}, \text{true}, S, 1} \oplus [C_v]_{\text{vacReq}, \text{isCnfrmd}, L, 2} \rangle \\ C_f &\stackrel{\text{def}}{=} \langle \{p_{f1}, p_{f2}, p_{f3}\}, [onVac?C_v : C_n]_{\text{firePutout}, \text{true}, L, 1} \oplus [C_v]_{\text{vacRequest}, \text{isPutout}, L, 2} \rangle \\ C_v &\stackrel{\text{def}}{=} \langle \{p_{v1}, p_{v2}, p_{v3}, p_{v4}, p_{v5}\}, [C_f]_{\text{fire}, \text{true}, S, 1} \oplus [C_n]_{\text{comebackHome}, \text{true}, L, 2} \rangle \end{aligned}$$

## 5 Operational Semantics of PobsAM

### 5.1 Operational Semantics of Actors and Views

The operational semantics of our extension of Rebeca does not differ from that of Rebeca[15]. However, any changes in state of the rebecs used in the definition of views must be reflected to the views. Let  $I_1, I_2, \dots, I_n$  denote the defined views of SMM  $S$  and  $\eta$  denote the set of defined events that  $S$  is concerned with. The state of a view is determined by its current value that is modified by the related events occurring at the actor level. After execution of a message server, the changes of public state variables must be reflected in the views state, too. We specify the operational semantics of the view layer as a labeled transition system.

Let  $S_B, A_B$  and  $T_B \subseteq S_B \times A_B \times S_B$  be the set of states, the set of actions and the state transition relation of the transition system of the actor layer respectively. The state transition relation of the view layer  $T_I \subseteq S_I \times A_I \times S_I$  is defined based on  $T_B$ , where  $S_I$  and  $A_I$  are the set of states and the set of actions of the view layer transition system respectively and  $S_I = \langle I_1, I_2, \dots, I_n \rangle$ . Suppose  $I_j(x_1, x_2, \dots, x_m)$  denotes an arbitrary view defined on public state variables  $x_1, x_2, \dots, x_m$  and  $I_j|_{\sigma_s}$  denotes the state of  $I_j$ , where its state variables are substituted with their corresponding values in state  $\sigma_s$  in  $S_B$ . For each triple  $\langle \sigma_s, a, \sigma_t \rangle \in T_B$ , we consider an associated transition  $\langle \sigma'_s, a, \sigma'_t \rangle \in T_I$  where  $\sigma'_s = \langle I_1|_{\sigma_s}, I_2|_{\sigma_s}, \dots, I_n|_{\sigma_s} \rangle$  and  $\sigma'_t = \langle I_1|_{\sigma_t}, I_2|_{\sigma_t}, \dots, I_n|_{\sigma_t} \rangle$  if and only if  $a \in \eta$  or  $\exists I_k | 1 \leq k \leq n \wedge I_k|_{\sigma_s} \neq I_k|_{\sigma_t}$ , i.e.

$$\frac{\sigma_s \xrightarrow{a} \sigma_t \in T_B, (a \in \eta) \vee (\exists I_k | 1 \leq k \leq n \wedge I_k|_{\sigma_s} \neq I_k|_{\sigma_t})}{\sigma'_s \xrightarrow{a} \sigma'_t}$$

$$\begin{array}{c}
 \text{(NPE1)} \frac{\mathcal{R} = \{p \mid (p.\varepsilon \wedge p.\psi) = \text{true}\} \wedge \mathcal{R} \neq \emptyset}{\mathcal{M}_{\emptyset, \emptyset} C[0] \xrightarrow{\varepsilon, \tau} [\mathcal{M}]_{\mathcal{R}, \emptyset} C[0]} \quad \text{(NPE2)} \frac{p \in \mathcal{R} \wedge (\nexists q \in \mathcal{R} \mid q.o > p.o)}{[\mathcal{M}]_{\mathcal{R}, \emptyset} C[0] \xrightarrow{p.\varepsilon \wedge p.\psi, \text{enf}(p)} [\mathcal{M}]_{\mathcal{R}, p} C[p.\alpha]} \\
 \text{(NPE3)} \frac{\alpha \longrightarrow \alpha'}{[\mathcal{M}]_{\mathcal{R}, p} C[\alpha + \beta] \xrightarrow{\text{true}, \tau} [\mathcal{M}]_{\mathcal{R}, p} C[\alpha']} \\
 \text{(NPE4)} \frac{}{[\mathcal{M}]_{\mathcal{R}, p} C[[\omega? \alpha : \beta]] \xrightarrow{\omega, \tau} [\mathcal{M}]_{\mathcal{R}, p} C[\alpha]} \quad \text{(NPE5)} \frac{}{[\mathcal{M}]_{\mathcal{R}, p} C[[\omega? \alpha : \beta]] \xrightarrow{\neg \omega, \tau} [\mathcal{M}]_{\mathcal{R}, p} C[\beta]} \\
 \text{(NPE6)} \frac{\alpha \longrightarrow \alpha'}{[\mathcal{M}]_{\mathcal{R}, p} C[\alpha \parallel \beta] \xrightarrow{\text{true}, \tau} [\mathcal{M}]_{\mathcal{R}, p} C[\alpha' \parallel \beta]} \\
 \text{(NPE7)} \frac{}{[\mathcal{M}]_{\mathcal{R}, p} C[r.\ell(v); r'.\ell'(v')] \xrightarrow{\ell, \ell' \notin \{\text{sendAck}, \text{waitAck}\}, \tau} [\mathcal{M}]_{\mathcal{R}, p} C[r.\ell(v); r.\text{sendAck}(r'); r'.\text{waitAck}(\text{sendAck}(r')); r'.\ell'(v')]} \\
 \text{(NPE8)} \frac{}{[\mathcal{M}]_{\mathcal{R}, p} C[r.\ell(v); \beta] \xrightarrow{\text{true}, \text{send}(r, \ell(v))} [\mathcal{M}]_{\mathcal{R}, p} C[\beta]} \\
 \text{(NPE9)} \frac{}{[\mathcal{M}]_{\mathcal{R}, p} C[0] \xrightarrow{\text{true}, \tau} [\mathcal{M}]_{\mathcal{R}-p, \emptyset} C[0]} \quad \text{(NPE10)} \frac{}{[\mathcal{M}]_{\emptyset, \emptyset} C[0] \xrightarrow{\text{true}, \tau} \mathcal{M}_{\emptyset, \emptyset} C[0]}
 \end{array}$$

Fig. 3. Rules of policy enforcement

## 5.2 Operational Semantics of Managers

We use a labeled transition system to define the operational semantics of managers in which labels have two components. The first component indicates the activation condition of the transition while the second component denotes the action of the transition. Assume that  $M$  is a logical expression defined on state variables, the transitions are of the form  $P \xrightarrow{M, a} Q$  meaning “if  $M$  holds then  $P$  has an action  $a$  leading to  $Q$ ”. Henceforth, we denote a transition by  $P \xrightarrow{\mu} Q$  where  $\mu = (M, a)$ .

The behavior of a manager depends on the mode in which it is running. A manager can run in different modes such as normal execution, adaptation and policy enforcement. To distinguish managers in different modes, we use different notations. Let  $[\mathcal{M}]_{\mathcal{R}, p}^s C[\alpha]$  indicate manager  $\mathcal{M}$  in the enforcement mode in which,

- $C$  is the configuration in which  $\mathcal{M}$  is running and  $C \stackrel{\text{def}}{=} \langle P, A \rangle$ .
- $\mathcal{R}$  is the set of triggered policies to be enforced.
- $p$  is the current policy being enforced by  $\mathcal{M}$ .
- $\alpha$  is the action of a recent policy being executed by  $\mathcal{M}$ .
- $s$  denotes  $\mathcal{M}$ 's view of current context in addition to its local variables.

$\mathcal{M}_{\emptyset, \emptyset}^s C[0]$ ,  $[\mathcal{M}]_{\mathcal{R}, p}^s C[\alpha]$  and  $[\mathcal{M}]_{\emptyset, \emptyset}^s C[0]$  indicate  $\mathcal{M}$  in normal execution, loose adaptation and strict adaptation modes respectively. We ignore  $s$  in the definition of operational semantics of managers.

### Policy enforcement semantics

Whenever an event is received by a manager, it identifies all the triggered policies with the policy condition evaluated to true. Then it enforces the identified policies

based on their priorities. Once a manager enforces all the triggered policies, it evolves to normal mode. Figure 3 gives rules of policy enforcement.

Using NPE1 manager switches to the enforcement mode by identifying the triggered policies to be enforced. NPE2 places the action of a policy with the highest priority in the action part of the manager to be run. NPE3, NPE4 and NPE5 define the semantics of non-deterministic and conditional choices of actions. NPE7 is considered to apply two sequential actions in which  $r'$  is an arbitrary actor. To this aim, we use synchronous message passing provided by Extended Rebeca [16]. The corresponding actors of two sequential actions are synchronized after execution of the first action. We considered two message servers for each reactive class named  $sendAck(r)$  and  $waitAck(r)$  which sends and receives a synchronization message to and from rebec  $r$  respectively. NPE8 expresses sending a message to an actor and removing it from the list of actions to be executed. After applying policy  $p$ , NPE9 will remove  $p$  from the list of activated policies. When there is no policy to be enforced, manager will switch to normal execution mode using NPE10.

As mentioned above, managers in loose adaptation mode are able to enforce policies. Therefore, all the rules introduced for the enforcement mode, except for NPE10, are applicable in loose adaptation mode too.

### Policy adaptation semantics

For the sake of readability, we omit  $p$ ,  $[a]$  and  $\mathcal{R}$  symbols of managers in normal execution and strict adaptation modes. Figure 4 shows rules for adaptation in strict mode in which  $B$ ,  $A'$  and  $B'$  denote arbitrary adaptation policies. Furthermore,  $F$  and  $D''$  denote a simple adaptation policy and an arbitrary configuration, respectively.

$$\begin{aligned}
 \text{(SA1)} & \frac{\nexists F \in A | (\vartheta < F.\vartheta \wedge F.\delta = true)}{\mathcal{M}\langle P, [D]_{\delta,\gamma,\lambda,\vartheta} \oplus A \rangle \xrightarrow{\delta \wedge \lambda, \tau} \|\mathcal{M}\|\langle P, [D]_{\delta,\gamma,\lambda,\vartheta} \rangle} \\
 \text{(SA2)} & \frac{}{\|\mathcal{M}\|\langle P, [D]_{\delta,\gamma,\lambda,\vartheta} \rangle \xrightarrow{\gamma, adapt} \mathcal{M}_{\emptyset, \emptyset} D} \\
 \text{(SA3)} & \frac{\mathcal{M}\langle P, B \rangle \xrightarrow{\mu} \mathcal{M}\langle P, B' \rangle}{\mathcal{M}\langle P, A \oplus B \rangle \xrightarrow{\mu} \mathcal{M}\langle P, A \oplus B' \rangle} \quad \text{(SA4)} \frac{\mathcal{M}\langle P, A \rangle \xrightarrow{\mu} \mathcal{M}\langle P, A' \rangle}{\mathcal{M}\langle P, A \oplus B \rangle \xrightarrow{\mu} \mathcal{M}\langle P, A' \oplus B \rangle} \\
 \text{(SA5)} & \frac{\|\mathcal{M}\|\langle P, [D]_{\delta,\gamma,\lambda,\vartheta} \rangle \xrightarrow{\mu} \|\mathcal{M}\|\langle P, [D']_{\delta,\gamma,\lambda,\vartheta} \rangle}{\|\mathcal{M}\|\langle P, [D \square D'']_{\delta,\gamma,\lambda,\vartheta} \rangle \xrightarrow{\mu} \|\mathcal{M}\|\langle P, [D']_{\delta,\gamma,\lambda,\vartheta} \rangle} \\
 \text{(SA6)} & \frac{\|\mathcal{M}\|\langle P, [D]_{\delta,\gamma,\lambda,\vartheta} \rangle \xrightarrow{\mu} \|\mathcal{M}\|\langle P, [D']_{\delta,\gamma,\lambda,\vartheta} \rangle}{\|\mathcal{M}\|\langle P, [D'' \square D]_{\delta,\gamma,\lambda,\vartheta} \rangle \xrightarrow{\mu} \|\mathcal{M}\|\langle P, [D']_{\delta,\gamma,\lambda,\vartheta} \rangle} \\
 \text{(SA7)} & \frac{}{\|\mathcal{M}\|\langle P, [\omega?D:D']_{\delta,\gamma,\lambda,\vartheta} \rangle \xrightarrow{\omega, \tau} \|\mathcal{M}\|\langle P, [D]_{\delta,\gamma,\lambda,\vartheta} \rangle} \\
 \text{(SA8)} & \frac{}{\|\mathcal{M}\|\langle P, [\omega?D:D']_{\delta,\gamma,\lambda,\vartheta} \rangle \xrightarrow{\neg\omega, \tau} \|\mathcal{M}\|\langle P, [D']_{\delta,\gamma,\lambda,\vartheta} \rangle}
 \end{aligned}$$

Fig. 4. Rules of strict adaptation

SA1 states that in the case of strict adaptation, when adaptation policy conditions hold, manager  $\mathcal{M}$  switches to the strict adaptation mode. SA2 asserts that

when the condition for applying the adaptation holds,  $\mathcal{M}$  will evolve to normal mode and run configuration D. SA5, SA6, SA7 and SA8 define the semantics of non-deterministic and conditional choices of configurations. SA5, SA6, SA7 and SA8 rules have a higher priority than SA2. To this aim, we use the ordered SOS (Structural Operational Semantics) framework [17] and place SA5, SA6, SA7 and SA8 above SA2. Rules of loose adaptation are identical to strict adaptations rules except for SA1 which is as 
$$\frac{\nexists F \in A | (\vartheta < F.\vartheta \wedge F.\delta = true)}{\mathcal{M}\langle P, [D]_{\delta,\gamma,\lambda,\vartheta} \oplus A \rangle \xrightarrow{\delta \wedge \neg \lambda, \tau} |\mathcal{M}| \langle P, [D]_{\delta,\gamma,\lambda,\vartheta} \rangle} \text{(LA1)}$$

### 5.3 Interaction of Managers and Views

The other kind of transitions is related to the interaction of managers and view layer. Figure 5 demonstrates rules for interaction of managers and the view layer of  $S$  where  $\sigma_s \xrightarrow{a} \sigma_t \in T_1$  and  $t$  indicates the new state of  $M$ .  $s_v$  and  $t_v$  are defined as the projection of  $\sigma_s$  and  $\sigma_t$  on  $M$ 's view respectively, i.e.  $s_v = \sigma_s \uparrow M.v$  and  $t_v = \sigma_t \uparrow M.v$ . Construct  $\sigma_s \uparrow M.v$  denotes only the state variables of  $\sigma_s$  that are in  $M.v$  too. IR1, IR2, IR3 and IR4 express changing  $\mathcal{M}$ 's view of the view layer by state changing at the view layer in the normal, enforcement, loose adaptation and strict adaptation modes respectively, where  $s(t)$  is union of  $s_v(t_v)$  and  $lv$ .  $lv$  indicates the current state of  $M$  in terms of its local variables.

$$\begin{array}{ll} \text{(IR1)} \frac{\sigma_s \xrightarrow{a} \sigma_t, \exists I_j \in s | I_j |_{\sigma_s} \neq I_j |_{\sigma_t}}{\mathcal{M}_{\emptyset, \emptyset}^s \langle P, A \rangle [0] \xrightarrow{true, \tau} \mathcal{M}_{\emptyset, \emptyset}^t \langle P, A \rangle [0]} & \text{(IR2)} \frac{\sigma_s \xrightarrow{a} \sigma_t, \exists I_j \in s | I_j |_{\sigma_s} \neq I_j |_{\sigma_t}}{[\mathcal{M}]_{\emptyset, \emptyset}^s \langle P, A \rangle [0] \xrightarrow{true, \tau} [\mathcal{M}]_{\emptyset, \emptyset}^t \langle P, A \rangle [0]} \\ \text{(IR3)} \frac{\sigma_s \xrightarrow{a} \sigma_t, \exists I_j \in s | I_j |_{\sigma_s} \neq I_j |_{\sigma_t}}{|\mathcal{M}|_{\mathcal{R}, p}^s \langle P, A \rangle [0] \xrightarrow{true, \tau} |\mathcal{M}|_{\mathcal{R}, p}^t \langle P, A \rangle [0]} & \text{(IR4)} \frac{\sigma_s \xrightarrow{a} \sigma_t, \exists I_j \in s | I_j |_{\sigma_s} \neq I_j |_{\sigma_t}}{\|\mathcal{M}\|_{\emptyset, \emptyset}^s \langle P, A \rangle [0] \xrightarrow{true, \tau} \|\mathcal{M}\|_{\emptyset, \emptyset}^t \langle P, A \rangle [0]} \end{array}$$

Fig. 5. Rules for interaction of managers and the view layer

## 6 Discussion and Related Work

Flexibility of self-adaptive systems is realized by three different features including separation of concerns, computational reflection and component-based design [18]. We explain how PobSAM can address these requirements in the sequel.

PobSAM decouples the adaptation logic of an SMM from its business logic described at an abstract level using policies. Among the proposed formal approaches to model adaptive systems, [2,20,21] combine the adaptation logic into the business logics. In [3,6,19] the adaptation concerns have been separated; however, all the proposed formal models hard-code the adaptation logic which leads to system's inflexibility. The proposed model permits us to direct/adapt system behavior by enforcing/modifying policies at an abstract level without re-coding actors and managers; thereby it leads to increasing system flexibility and scalability.

Computational reflection is the ability of a system to monitor and change its behavior subsequently. In PobSAM, managers monitor actor's behavior through views and direct/adapt SMMs behavior. Policies provide us a high-level description of what we want without dealing with how to achieve it. Thus, using policies can be a suitable mechanism to determine if the goals were achieved using existing policy refinement techniques.

Furthermore, PobsAM uses SMM as a policy-based building block for a modular model where each component is able to adapt its behavior autonomously. This notion makes PobsAM a suitable model to specify self-organizing and cooperating systems too. Although, in this paper we focused on behavioral adaptation, however, PobsAM can support structural adaptation by joining/leaving an actor or an SMM to/from an SMM dynamically, which is an advantage over the most existing approaches that concentrate on one adaptation type. SMM notion is similar to Self-Managed Cell (SMC) notion proposed in [13] as a paradigm for engineering ubiquitous systems. In this work, an SMC consists of a set of components that constructs an autonomous management domain.

One of the main aspects of modeling a self-adaptive system is specifying adaptation requirements. To this aim, we introduced a two phases adaptation strategy to pass the adaptation phase safely. Upon receiving an adaptation event by a manager, it switches to the adaptation mode. Adaptation mode models transient states during adaptation. When the system reaches a safe state, the adaptation is completed by evolving the manager to the new configuration. We believe that the modular nature of adaptation policies enables us to express adaptation requirements easily and at the high-level of abstraction.

As stated above, PobsAM has decoupled the adaptation layer from the functional layer. Thus, we can verify the adaptation layer independently from the actor layer provided that we have a labeled transition system modeling view behavior. This feature can decrease the complexity of verification procedure.

Dynamic adaptation is a very diverse area of research. While structural adaptation has been given strong attention in the research community(see [22]), fewer approaches tackle behavioral adaptation as we considered. Due to the lack of space, we restrict ourselves to present related work done on formal modeling of self-adaptive systems in addition to applying policy-based approaches in engineering of self-adaptive systems.

Formal verification of adaptive systems is a young research area [23] and only a few research groups already focused on this topic. A model-driven approach was proposed for developing adaptive systems in [2]. In this approach, there are different behavioral variants of a process modeled as Petri Nets. At each time, one Petri Net runs and reconfiguration is carried out by switching between various Petri Nets. In another work [3], they modeled a system as a set of steady-state programs among which the system switches. An extension of LTL with “adapt“ operator was used to specify adaptation requirements before, during and after adaptation [4]. Then, they use a model checking approach to verify the system. Kulkarni et al. [7] proposed an approach based on the concept of proof lattice to verify if a system is in a correct state during and after adaptation in terms of satisfying the transitional-invariants. Furthermore, Schneider et al. [5] presented a method to describe adaptation behavior at an abstract level. After deriving transition systems from a system description, they verify the system using model checking. In their later work [6], they proposed a framework for model-based development of adaptive embedded systems using labeled transition systems. In this work, they verify different properties using theorem proving, model checking and specialized verification methods. [19] proposed a coordination protocol for distributed adaptation of the

component-based systems and used Colored Petri Nets for formal verification. In our model, adaptation is performed by applying suitable policies in different contexts, which in nature differs from the proposed approaches. We have proposed a formal model of policy-based self-adaptive systems using Rebeca concentrated on policy conflict detection [14]. Combining adaptation concerns with system functionality in this approach causes an increase in the complexity of model as well as formal verification process.

Employing policies as a paradigm to adapt self-adaptive systems has been given considerable attention during recent years. Work in [8,9,10,11,24,26] used policies as the adaptation logic for structural adaptation, while we use policies as a mechanism for governing as well as adapting system behavior. Furthermore, [24] used policies for a simple type of behavioral adaptation named parameterization, too. [25] proposed an adaptive architecture for management of differentiated networks which performs adaptation by enabling/disabling a policy from a set of predefined QoS policies, but this architecture does not have formal foundation. Anthony [26] presents a policy definition language for autonomic computing systems in which the policies themselves can be modified dynamically to match environmental conditions. However, this work does not deal with modeling system and it is limited to proposing an informal policy language.

## 7 Conclusions and Future Work

We proposed PobSAM as a formal model to develop self-adaptive systems which uses policies as the main mechanism to govern and adapt the system behavior. To this aim, we model a system as the composition of a set of autonomous components named SMMs. Each SMM contains two types of actors: managed actors that are dedicated to the functional layer of system and autonomous managers that coordinate actors to achieve the predefined goals using policies. This model integrates two formal methods including algebra and actor-based model to specify a system. Then, we presented the operational semantics of PobSAM by means of labeled transition systems.

There is much more research to pursue in the area of verification of self-adaptive systems. In this paper, we focused on formal modeling of self-adaptive systems. Verification of different properties of adaptation and functional layers of PobSAM models is an ongoing work. We are going to implement a tool to support our approach too. As our model can support both behavioral and structural adaptations, our future researches will be concentrated on specifying structural adaptations. Extending this model for modeling self-organizing systems in which managers need to coordinate together is considered as a future work, too.

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