



CAMEL Documentation v2015.9

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Executive Summary

Cloud computing provides ubiquitous networked access to a shared and virtualised pool of computing capabilities that can be provisioned with minimal management effort [23]. Cloud applications are deployed on cloud infrastructures and delivered as services. The PaaSage project aims to facilitate the modelling and execution of cloud applications by leveraging model-driven engineering (MDE) and by exploiting multiple cloud infrastructures. Models enable the abstraction from the implementation details of heterogeneous cloud services, while model transformations facilitate the automatic generation of the source code that exploits these services. The Cloud Application Modelling and Execution Language (CAMEL) is the core modelling and execution language developed in the PaaSage project and enables the specification of multiple aspects of cross-cloud applications (*i.e.*, applications deployed across multiple private, public, or hybrid cloud infrastructures). By exploiting models at both design- and runtime, and by allowing both direct and programmatic manipulation of models, CAMEL enables the management of self-adaptive cross-cloud applications (*i.e.*, cross-cloud applications that autonomously adapt to changes in the environment, requirements, and usage). In this document, we describe the design and implementation of CAMEL. Moreover, we provide a real-world running example to illustrate how to specify models in a concrete textual syntax and how to programmatically manipulate and persist them through Java APIs.

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1 Introduction

MDE is a branch of software engineering that aims to improve the productivity, quality, and cost-effectiveness of software development by shifting the paradigm from code-centric to model-centric. MDE promotes the use of models and model transformations as the primary assets in software development, where they are used to specify, simulate, generate, and manage software systems. This approach is particularly relevant when it comes to the modelling and execution of cross-cloud applications (*i.e.*, applications deployed across multiple private, public, or hybrid cloud infrastructures). This solution allows to exploit the peculiarities of each cloud service and hence to optimise the performance, availability, and cost of the applications.

Models can be specified using general-purpose languages like the Unified Modeling Language (UML) [27]. However, to fully unfold the potential of MDE, models are frequently specified using domain-specific languages (DSLs), which are tailored to a specific domain of concern. The PaaSage¹ project exploits the latter approach and provides an integrated platform to support the modelling and execution of cross-cloud applications. To achieve this goal, PaaSage developed the Cloud Application Modelling and Execution Language (CAMEL). This DSL allows to specify multiple aspects of cross-cloud applications, such as provisioning, deployment, service level, monitoring, scalability, providers, organisations, users, roles, security, and execution.

CAMEL supports the models@run-time [5] approach, which provides an abstract representation of the underlying running system, whereby a modification to the model is enacted on-demand in the system, and a change in the system is automatically reflected in the model.

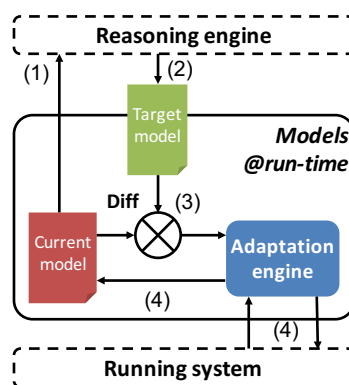


Figure 1: Models@run-time architecture

¹<http://www.paasage.eu>

Fig. 1 depicts the architecture of models@run-time. A reasoning engine reads the current model (step 1) and produces a target model (step 2). Then, the run-time environment computes the difference between the current model and the target one (step 3). Finally, the adaptation engine enacts the adaptation by modifying only the parts of the cross-cloud application necessary to account for the difference and the target model becomes the current model (step 4).

CAMEL was designed and implemented to allow the design-time specification of models by users as well as their run-time manipulation by reasoners. By exploiting models at both design- and run-time, and by allowing both direct and programmatic manipulation of models, CAMEL enables the management of self-adaptive cross-cloud applications (*i.e.*, cross-cloud applications that autonomously adapt to changes in the environment, requirements, and usage). This represents the main motivation for our research and contribution of our work, since, to the best of our knowledge, no other integrated language in the literature supports the management of self-adaptive cross-cloud applications (see Section 17).

Structure of the document: The remainder of the document is organised as follows. Section 2 describes the role of CAMEL models in a self-adaptation workflow. Section 3 presents some technologies used to design and implement CAMEL. Section 4 provide instructions for installing and using the CAMEL Textual Editor. Sections 5–15 present the various packages of the CAMEL metamodel along with corresponding sample models in concrete syntax. Section 16 exemplifies the usage of Java APIs to programmatically manipulate and persist models. Finally, Section 17 compares the proposed approach with related work, while Section 18 draws conclusions and outlines plans for future work.

2 CAMEL and the Self-Adaptation Workflow

The components managing the life cycle of cross-cloud applications are integrated by leveraging CAMEL models. These models are progressively refined throughout the *modelling*, *deployment*, and *execution* phases of a self-adaptation workflow based on the models@run-time approach, as proposed in PaaSage [33].

Figure 2 shows the self-adaptation workflow. The *white trapezes* represent the activities performed by the user. The *white rectangles* represent the processes executed by the PaaSage platform. The *coloured shapes* represent the modelling artefacts, whereby the blue ones pertain to the modelling phase, the red ones to the deployment phase, and the green ones to the execution phase.

In the remainder of the document, we adopt the Scalarm² [21] use case as

²<http://www.scalarm.com/>

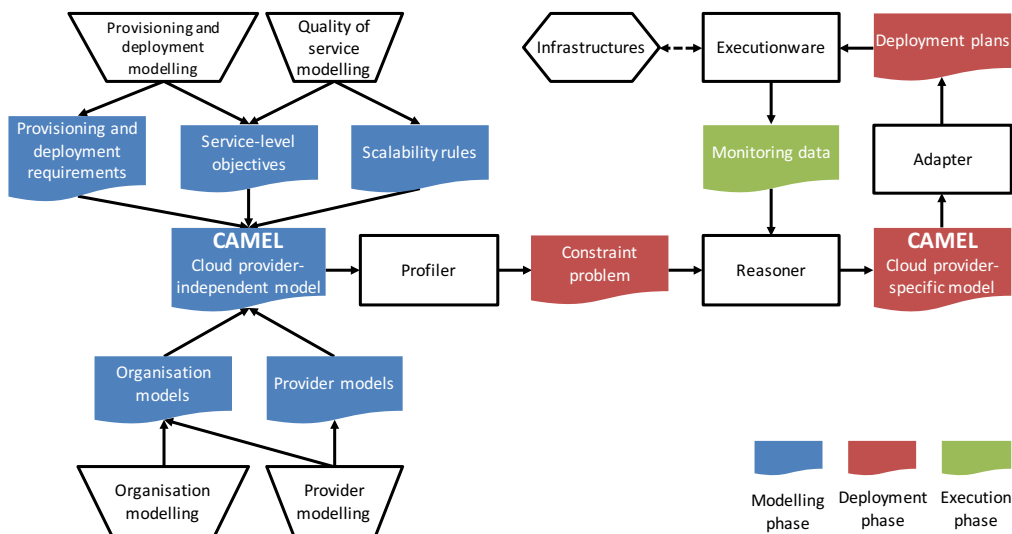


Figure 2: CAMEL models in the self-adaptation workflow

a real-world running example to illustrate how to specify multiple aspects of cloud applications in CAMEL, and how these specifications facilitate the deployment of cloud applications across multiple clouds and their self-adaptation to changes in the environment, requirements, and usage. Scalarm is a massively self-scalable platform for data farming. Data farming experiments utilise high-performance and high-throughput computing to generate large amounts of data via simulations. These data are analysed to obtain new insights into the studied phenomena. The architecture of Scalarm is based on the principles of service-oriented architecture (SOA) and consists of the following services:

- *Experiment Manager* provides a graphical user interface to coordinate the execution of data farming experiments.
- *Simulation Manager* provides a wrapper to execute the simulations on multiple computational infrastructures.

As data farming experiments are often executed on a large amount of computational infrastructures and across multiple data centres, the Scalarm use case is particularly suitable to illustrate the features of CAMEL.

Modelling phase. The users design a *cloud provider-independent model* (CPIM), which specifies the deployment of a cross-cloud application along with its requirements and objectives (*e.g.*, on virtual hardware, location, and service level) in a cloud provider-independent way.

Figure 3(a) shows the CPIM of Scalarm in graphical syntax. It consists of an Experiment Manager (represented by ExpMan) hosted on a GNU/Linux virtual machine (represented by Linux). Moreover, the Experiment Manager communicates with a Simulation Manager (represented by SimMan) hosted on a GNU/Linux virtual machine in a data centre in Norway. Finally, the Experiment Manager has a service-level objective specifying that the response time must be below 100 ms.

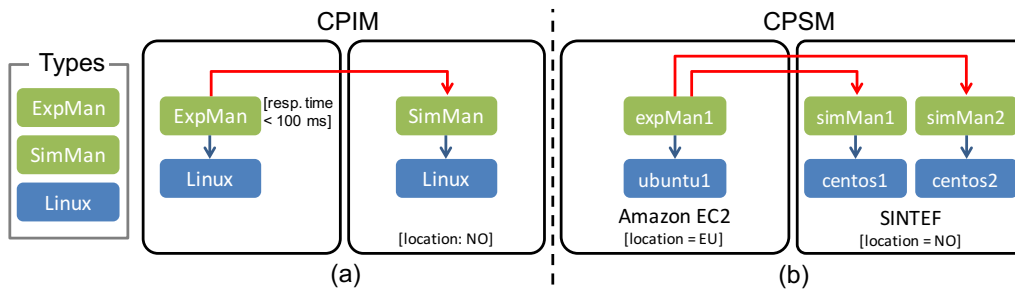


Figure 3: Sample CAMEL models: (a) CPIM; (b) CPSM

Deployment phase. The Profiler component consumes the CPIM, matches this model with the profile of cloud providers, and produces a *constraint problem*. The Reasoner component solves the constraint problem (if possible) and produces a *cloud provider-specific model* (CPSM), which specifies the deployment of a cross-cloud application along with its requirements and objectives in a cloud provider-specific way. The Adapter component consumes the CPSM and produces *deployment plans*, which specify the platform-specific details of the deployment.

For instance, the Profiler could match the CPIM of Scalarm with the profile of cloud providers, identify Amazon EC2, Google Compute Engine, and Azure as the three cloud providers satisfying the virtual hardware requirements and service-level objectives of the Experiment Manager (response time below 100 ms). Moreover, the Profiler could identify SINTEF³ and EVRY⁴ as the two cloud providers satisfying the virtual hardware and location requirements of the Simulation Manager (data centre in Norway), and produce a corresponding constraint problem. Then, the Reasoner could rank Amazon and SINTEF as the best cloud providers to satisfy these requirements and produce a corresponding CPSM.

Figure 3(b) shows the CPSM in graphical syntax. It consists of an Experiment Manager *instance*, which is hosted on a Ubuntu 14.04 instance at Amazon

³<https://www.sintef.no/en/>

⁴<https://www.cloudservices.no/>

EC2 in the EU. Moreover, the Experiment Manager instance communicates with two Simulation Manager instances, which are hosted on two CentOS 7 virtual machine instances at SINTEF in Norway.

Execution phase. The Executionware consumes the deployment plans and enacts the deployment of the application components on suitable cloud infrastructures. The PaaSage platform records monitoring data about the application execution from the Executionware, which allows the Reasoner to continuously revise the solution to the constraint problem to better exploit the cloud infrastructures.

3 Technologies

In order to design and implement CAMEL, we adopted the Eclipse Modeling Framework (EMF)⁵ along with Object Constraint Language (OCL) [26], Xtext⁶, and Connected Data Objects (CDO).⁷ In the following, we outline these technologies and describe how they facilitate the implementation of the PaaSage platform described in Section 2.

Eclipse Modeling Framework (EMF). In MDE, the abstract syntax of a DSL is typically defined by its metamodel, which describes the set of concepts, their attributes, and their relations, as well as the rules for combining these concepts to specify valid models conforming to this metamodel [27]. EMF is a modeling framework that facilitates defining DSLs. It provides the Ecore metamodel, which is an Ecore model that conforms to itself (*i.e.*, it is reflexive). The CAMEL metamodel is an Ecore model that conforms to the Ecore metamodel.

EMF allows to generate a Java class hierarchy representation of a metamodel. The Java representation provides a set of APIs that allows the programmatic manipulation of models.

Object Constraint Language (OCL). EMF enables to check the cardinality constraints on properties and to validate models against their metamodels. However, it lacks the expressiveness required to capture all of the semantics of the domain. OCL is a declarative language for specifying expressions on metamodels that are evaluated on models conforming to these metamodels. Eclipse OCL⁸ is a tool-supported implementation of OCL that integrates with EMF. The CAMEL

⁵<https://www.eclipse.org/modeling/emf/>

⁶<https://eclipse.org/Xtext/>

⁷<https://www.eclipse.org/cdo/>

⁸<http://wiki.eclipse.org/OCL>

metamodel is annotated with OCL expressions to capture part of the semantics of cross-cloud applications and to guarantee the consistency, correctness, and integrity of CAMEL models at both design-time and run-time.

Xtext. In MDE, the concrete syntax describes the textual or graphical notation that renders the concepts, attributes, and relations in the abstract syntax. The concrete syntax may vary depending on the domain, *e.g.*, a DSL could provide a textual notation as well as a graphical notation along with the corresponding serialisation in XML Metadata Interchange (XMI) [28]. Xtext is a language development framework that is based on- and integrates with EMF. It facilitates the implementation of Eclipse-based IDEs providing features, such as syntax highlighting, code completion, code formatting, static analysis, and serialisation. The concrete syntax of CAMEL is a textual syntax defined as an Xtext grammar. The textual syntax was preferred over the graphical syntax by the early adopters of CAMEL.

Connected Data Objects (CDO). CDO is semi-automated persistence framework that works natively with Ecore models and their instances. It provides a model repository where clients can persist, share, and query their models. It provides features that satisfy the design-time and run-time requirements of the self-adaptation workflow (see Section 2), such as abstraction from database management systems (DBMSs), validation, transactional processing, optimistic versioning [36], automatic notification, auditing, and role-based security [19].

Thanks to the combination of EMF, Eclipse OCL, and Xtext, we realised the CAMEL Textual Editor, which allows users not only to specify CAMEL models but also to validate them. Moreover, thanks to these technologies and CDO, we realised the *models@run-time* approach, which allows multiple reasoners to progressively refine CAMEL models throughout the various phases of the self-adaptation workflow (see Section 2).

4 Installation and Usage of CAMEL Textual Editor

In this section, we provide instructions for installing and using the CAMEL Textual Editor. These steps have been tested with the latest version of Eclipse, which at the time of writing is Eclipse Neon v4.6.0. We distinguish between the installation for users and for developers.

4.1 Installation—Users

- Download and install “Eclipse IDE for Java and **DSL** Developers” from: <https://www.eclipse.org/downloads/>
- Start Eclipse
- Select Help > Install New Software...
- Select Work with: Neon—<http://download.eclipse.org/releases/neon>
- Select Modeling > CDO Model Repository SDK
- Select Modeling > OCL Classic SDK: Ecore/UML Parsers,Evaluator,Edit
- Select Modeling > OCL Examples and Editors
- Install the three packages
- Download `org.ow2.paasage.camel_2015.9.1.jar`, `org.ow2.paasage.camel.dsl_2015.9.1.jar`, and `org.ow2.paasage.camel.dsl.ui_2015.9.1.jar` from: <http://jenkins.paasage.cetic.be/job/CAMEL/>
- Copy the three jar files to the `eclipse/plugins` folder
- Restart Eclipse

4.2 Installation—Developers

- Clone the CAMEL Git repository from: <https://tuleap.ow2.org/plugins/git/paasage/camel>
- Download and install “Eclipse IDE for Java and **DSL** Developers” from: <https://www.eclipse.org/downloads/>
- Start Eclipse
- Select Help > Install New Software...
- Select Work with: Neon—<http://download.eclipse.org/releases/neon>
- Select Modeling > CDO Model Repository SDK
- Select Modeling > OCL Classic SDK: Ecore/UML Parsers,Evaluator,Edit
- Select Modeling > OCL Examples and Editors

- Install the three packages
- Restart Eclipse
- Select Import > Existing Projects into Workspace
- Select Browse...
- Select the folder where you cloned the CAMEL Git repository
- Select Finish
- Select `eu.paasage.camel.dsl/src/eu.paasage.camel.dsl/GenerateCamelDsl.mwe2`
- Select Run As > MWE2 Workflow...
- Select `eu.paasage.camel.dsl`
- Select Run > Run As > Eclipse Application...

4.3 Usage

- Add a (general) project
- Add a new file (or open an existing one) with `.camel` extension to the project
- Accept to add the Xtext nature to the project
- Restart Eclipse
- **Read the remainder of this document**
- Edit the file

5 CAMEL Design and Syntax

CAMEL has been designed based on the following requirements, among others:

- *Cloud provider-independence* (R_1): CAMEL should support a cloud provider-agnostic specification of multiple aspects of cross-cloud applications (*i.e.*, provisioning, deployment, service level, monitoring, scalability, providers, organisations, users, roles, security, and execution). This will prevent vendor lock-in.

- *Separation of concerns (R_2)*: CAMEL should support loosely-coupled packages (or modules) corresponding to multiple aspects of cross-cloud applications. This will facilitate the development of models.
- *Reusability (R_3)*: CAMEL should support reusable types for multiple aspects of cross-cloud applications. This will ease the evolution of models.
- *Abstraction (R_4)*: CAMEL should provide an up-to-date, abstract representation of the running system. This will enable the reasoning, simulation, and validation of the adaptation actions before their enactment.

CAMEL is inspired by component-based approaches, which facilitate separation of concerns (R_2) and reusability (R_3). In this respect, deployment models can be regarded as assemblies of components exposing ports, and bindings between these ports.

In addition, CAMEL implements the *type-instance* pattern [1], which also facilitates reusability (R_3) and abstraction (R_4). This pattern exploits two flavours of typing, namely *ontological* and *linguistic* [22]. Figure 4 illustrates these two flavours of typing. SL (short for Small GNU/Linux) represents a reusable type of virtual machine. It is linguistically typed by the class VM (short for virtual machine). SL1 represents an instance of the virtual machine SL. It is ontologically typed by SL and linguistically typed by VMInstance.

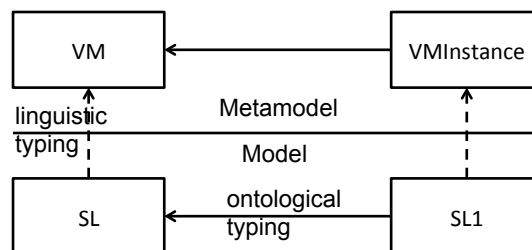


Figure 4: Linguistic and ontological typing

CAMEL and the CAMEL Textual Editor are available under Mozilla Public License 2.0⁹ in the Git repository at OW2.¹⁰ The CAMEL metamodel is an Ecore model organised into packages, whereby each package reflects an aspect (or domain).

As mentioned, in the remainder of the document, we adopt the Scalarm¹¹ [21] use case as a real-world running example to illustrate how to specify CAMEL

⁹<https://www.mozilla.org/en-US/MPL/2.0/>

¹⁰<https://tuleap.ow2.org/plugins/git/paasage/camel>

¹¹<http://www.scalarm.com/>

models in textual syntax. The complete Scalarm CAMEL model in textual syntax can be downloaded from the Git repository at OW2.¹² This running example covers the most commonly used concepts in CAMEL. The interested reader may refer to [35] for a complete description of the abstract syntax of CAMEL.

Listing 5.1: Scalarm sample application

```
1 camel model ScalarmModel {
2
3   application ScalarmApplication {
4     version: 'v1.0'
5     owner: AGHOrganisation.morzech
6     deployment models [ScalarmModel.ScalarmDeployment]
7   }
8
9   organisation model AGHOrganisation {
10    ...
11    user morzech {
12      ...
13    }
14  }
15
16  deployment model ScalarmDeployment {
17    ...
18  }
19 }
```

Listing 5.1 shows an excerpt of the CAMEL model of Scalarm in textual syntax. An element of a CAMEL model is specified by the name of the element followed by an identifier in CamelCase and a block delimited by curly brackets. `camel model ScalarmModel {...}` specifies the CAMEL model of Scalarm, where `ScalarmModel` represents the identifier of this model. `application ScalarmApplication` specifies the Scalarm application itself.

A property is specified by the name of the property followed by a colon and a value. `version: 'v1.0'` specifies that the Scalarm application has version 1.0.

A reference to a single element is specified by the name of the reference followed by a colon and a fully qualified name conforming to the pattern:

$id_1.id_2\dots id_n$, where id_i refers to element at the i^{th} level of the containment path and id_n refers to the element at the leaf level, which is the element under discussion. `owner: AGHOrganisation.morzech` specifies that the application is owned by the user Michal Orzechowski by referring to the user `morzech` in the organisation model `AGHOrganisation` (see Section 9, Listing 9.1).

Finally, a reference to a list of elements is specified by the name of the reference followed by a comma separated list of fully qualified names delimited by square brackets.¹³ `deployment models [ScalarmModel.ScalarmDeployment]` spe-

¹²<https://tuleap.ow2.org/plugins/git/paasage/camel?p=camel.git&a=blob&f=examples/Scalarm.camel>

¹³Note that the colon is not used in this case.

cifies that the Scalarm application has one deployment model by referring to the deployment model `ScalarmDeployment` (see Section 6, Listing 6.1).

6 Deployment

The deployment package of the CAMEL metamodel is based on CloudML¹⁴ [12, 10, 11], which was developed in collaboration with the MODAClouds project.¹⁵ CloudML consists of a tool-supported DSL for modelling and enacting the provisioning and deployment of cross-cloud applications, as well as for facilitating their dynamic adaptation, by leveraging MDE techniques and methods. In the following, we exemplify the main concepts in the deployment package.

Assume that we have to specify the Experiment Manager component of the Scalarm use case. Listing 6.1 shows this specification in textual syntax.

```
internal component ExperimentManager specifies a reusable type of the component Experiment Manager. provided communication ExpManPort specifies that the Experiment Manager provides its features through port 443. required communication SimManPortReq specifies that the Experiment Manager requires features from the Simulation Manager through port 80 (cf. Listing 6.3 for the corresponding specification of the communication binding). The property mandatory of SimManPortReq specifies that the Experiment Manager depends on the features of the Simulation Manager, and hence, that the Simulation Manager has to be deployed and started before the Experiment Manager. required host CoreIntensiveUbuntuNorwayReq specifies that the Experiment Manager requires a virtual machine that provides a large number of CPU cores, runs the operating system Ubuntu, and is located in Norway (cf. Listing 6.2 for the specification of the VM and VM requirements, and Listing 6.4 for the specification of the corresponding hosting binding).
```

```
configuration ExperimentManagerConfiguration specifies the commands to handle the life cycle of the Experiment Manager. download, install, and start specify the OS-specific shell scripts (in this case, Bash scripts) for downloading, installing, and starting the Experiment Manager, respectively. Note that, although not shown in this example, it is also possible to specify the configure and stop commands of a component.
```

The aforementioned commands are used by the Executionware during the execution phase to enact the deployment of the application components and to manage their life cycles (see Section 6.1).

Listing 6.1: Scalarm sample internal component

¹⁴<http://cloudml.org>

¹⁵<http://www.modaclouds.eu>

```

1 deployment model ScalarmDeployment {
2
3   internal component ExperimentManager {
4     provided communication ExpManPort {port: 443}
5     required communication SimManPortReq {port: 80 mandatory}
6     required host CoreIntensiveUbuntuNorwayHostReq
7
8     configuration ExperimentManagerConfiguration {
9       download: 'wget http://www.scalarm.com/scalarm_exp_man.sh &&
        chmod +x scalarm_exp_man.sh'
10      install: './scalarm_exp_man.sh install'
11      start: './scalarm_exp_man.sh start'
12    }
13  }
14  ...

```

Then, assume that we have to specify the virtual machine on which the Experiment Manager can be deployed. Listing 6.2 shows this specification in textual syntax.

`vm CoreIntensiveUbuntuNorway` specifies a reusable type for a virtual machine. `requirement set` refers to the aforementioned requirement set `CoreIntensiveUbuntuNorwayRS`. `provided host CoreIntensiveUbuntuNorwayPort` specifies that the virtual machine provides a large number of CPU cores, runs the operating system Ubuntu, and is located in Norway (*cf.* Listing 6.4 for the specification of the corresponding hosting binding).

`requirement set CoreIntensiveUbuntuNorwayRS` specifies a reusable set of requirements for a virtual machine. `quantitative hardware`, `os`, and `location` refer to the requirements `CoreIntensive`, `Ubuntu`, and `NorwayReq`, respectively, in the requirement model `ScalarmRequirement` (*cf.* Listing 7.1), which in turn specify the hardware requirements encompassing a large number of CPU cores, the operating system requirement of Ubuntu, and the location requirement of Norway, respectively.

Listing 6.2: Scalarm sample vm

```

1 ...
2 vm CoreIntensiveUbuntuNorway {
3   requirement set CoreIntensiveUbuntuNorwayRS
4   provided host CoreIntensiveUbuntuNorwayPort
5 }
6
7 requirement set CoreIntensiveUbuntuNorwayRS {
8   quantitative hardware: ScalarmRequirement.CoreIntensive
9   os: ScalarmRequirement.Ubuntu
10  location: ScalarmRequirement.NorwayReq
11 }
12 ...

```

Next, assume that we have to specify the communication binding between the Experiment Manager and the Simulation Manager. Listing 6.3 shows this

specification in textual syntax.

`communication ExperimentManagerToSimulationManager` specifies a reusable type of communication binding between the Experiment Manager and the Simulation Manager. The `from .. to ..` block specifies that the communication binding is from the required communication port `SimManPortReq` of the component `ExperimentManager` to the provided communication port `SimManPort` of the component `SimulationManager`. `type: REMOTE` specifies that the Experiment Manager and the Simulation Manager must be deployed on separate virtual machine instances. Note that this property could have a value `ANY` (default) to specify that the components at each end of the communication can be deployed on any virtual machine instance(s), or `LOCAL` to specify that the components must be deployed on the same virtual machine instance.

Listing 6.3: Scalarm sample communication

```
1 ...
2 communication ExperimentManagerToSimulationManager {
3     from ExperimentManager.SimManPortReq to SimulationManager.
      SimManPort
4     type: REMOTE
5 }
6 ...
```

Finally, assume that we have to specify the hosting binding between the Experiment Manager and the virtual machine `CoreIntensiveUbuntuNorway`. Listing 6.4 shows this specification in textual syntax.

`hosting ExperimentManagerToCoreIntensiveUbuntuNorway` specifies a reusable type of hosting binding between the Experiment Manager and the virtual machine `CoreIntensiveUbuntuNorway`. The `from .. to ..` block specifies that the hosting binding is from the required hosting port `CoreIntensiveUbuntuNorwayPortReq` of the component `ExperimentManager` to the provided hosting port `CoreIntensiveUbuntuNorwayPortReq` of the virtual machine `CoreIntensiveUbuntuNorway`.

Listing 6.4: Scalarm sample hosting

```
1 ...
2 hosting ExperimentManagerToCoreIntensiveUbuntuNorway {
3     from ExperimentManager.CoreIntensiveUbuntuNorwayPortReq to
      CoreIntensiveUbuntuNorway.CoreIntensiveUbuntuNorwayPort
4 }
5 ...
```

The types presented above can be instantiated in order to form a CPSM. In PaaSage, the instances within the deployment model are automatically manipulated during the deployment phase (see Section 2). In the general case, the instances could also be manipulated manually. Note that different CPSMs can adopt different instantiation patterns for communications and hosting bindings,

while still conforming to the same CPIM. The interested reader may refer to [7] for an extensive discussion on the subject.

Listing 6.5 shows the specification of instances of the components, virtual machines, communications, and hosting bindings from the previous examples (*cf.* Listings 6.1, 6.2, 6.3, and 6.4) in textual syntax.

`vm instance CoreIntensiveUbuntuNorwayInst` specifies an instance of a virtual machine. `vm type` and `vm type value` refer to the virtual machine flavour `M1.LARGE` in the provider model `SINTEFProvider` (*cf.* Listing 10.1), which is compatible with the requirement set of the virtual machine template `CoreIntensiveUbuntuNorway` (*cf.* Listing 7).

`internal component instance ExperimentManagerInst` specifies an instance of the component `ExperimentManager`. The `connect .. to .. typed ..` and `host .. on .. typed ..` blocks specify instances of the communication `ExperimentManagerToSimulationManager` and the hosting `ExperimentManagerToCoreIntensiveUbuntuNorway`, respectively. `typed` refers to the identifier of the corresponding type.

Listing 6.5: Scalarm sample instances of internal component, vm, communication, and hosting

```

1  ...
2  vm instance CoreIntensiveUbuntuNorwayInst typed ScalarmModel.
   ScalarmDeployment.CoreIntensiveUbuntuNorway {
3    vm type: ScalarmModel.SINTEFProvider.SINTEF.VM.VMType
4    vm type value: ScalarmModel.SINTEFType.VMTypeEnum.M1.LARGE
5    provided host instance CoreIntensiveUbuntuNorwayHostInst typed
   CoreIntensiveUbuntuNorway.CoreIntensiveUbuntuNorwayHost
6  }
7
8  internal component instance SimulationManagerInst typed ScalarmModel
   .ScalarmDeployment.SimulationManager {
9    provided communication instance SimManPortInst typed
   SimulationManager.SimManPort
10   required host instance SimulationIntensiveUbuntuNorwayHostReqInst
   typed SimulationManager.SimulationIntensiveUbuntuNorwayHostReq
11  }
12
13 internal component instance ExperimentManagerInst typed ScalarmModel
   .ScalarmDeployment.ExperimentManager {
14   provided communication instance ExpManPortInst typed
   ExperimentManager.ExpManPort
15   required communication instance SimManPortReqInst typed
   ExperimentManager.Si,ManPortReq
16   required host instance CoreIntensiveUbuntuNorwayHostReqInst typed
   ExperimentManager.CoreIntensiveUbuntuNorwayHostReq
17  }
18
19 connect ExperimentManagerInst.SimManPortReqInst to
   SimulationManagerInst.SimManPortInst typed ScalarmModel.
   ScalarmDeployment.ExperimentManagerToSimulationManager
20

```

```
21 host ExperimentManagerInst.CoreIntensiveUbuntuNorwayHostReqInst on  
    CoreIntensiveUbuntuNorwayInst.CoreIntensiveUbuntuNorwayHostInst  
    typed ScalarmModel.ScalarmDeployment.  
    ExperimentManagerToCoreIntensiveUbuntuNorway  
22 ...
```

6.1 Interplay with Executionware

In order to execute a cloud application, the Executionware provisions VMs, deploys one or more component instances on these VMs, and starts these instances by relying on a cross-cloud orchestration framework. In PaaSage, this cross-cloud orchestration framework is Cloudiator [6]. Note the Executionware can solely rely on the information provided in a CAMEL model. Hence, the Executionware does not make any assumptions besides the information provided.

In order to steer the individual instances of internal components, the Executionware relies on handlers that have been specified in the configuration of an internal component. The handlers are invoked in the following order:

1. download
2. install
3. configure
4. start

6.1.1 Life Cycle Scripts for Unix-based Applications

As stated above, the Executionware relies on the deployment model within a CAMEL model, and in particular on the configuration block of internal components, in order to manage the component instances. For GNU/Linux deployments, all of the handlers are executed as a single Unix shell script (*e.g.*, compatible with Bash) that has to be specified in the configuration block of internal components (*e.g.*, for downloading the executable code of the component). A return value different from 0 is interpreted as an error and causes the component instance to move to an error state. Data about ports and connection information as well as the local host is provided via environment variables.

Note that the different handlers are not necessarily executed in the very same instance of the Unix shell. This means that custom environment variables set in a handler (*e.g.*, in the `download` command) are not necessarily available in later handlers. If such information is required, the only approach is to write the necessary data to a file and source this file in later handlers. For GNU/Linux

deployments, all component instances are run within an own Docker container¹⁶ in order to enable a maximum of isolation between the instances. This has a consequence for user handling and networking: As for the users, this means that all commands are executed as `root`. Also, the handlers cannot assume that any other user beside `root` exists in the system. Hence, if further users are required, the handlers are responsible for creating them. As for networking, the effects on both IP addresses and port numbers are discussed in the following.

IP Addresses in the Execution Environment. First, all components have at least two IP addresses, namely the IP address of their Docker container and the IP address of the virtual machine this container is hosted on. Often, the IP of the virtual machine is a cloud-internal IP address that is not routed outside the cloud provider. Hence, it is very likely that there is a third IP address involved that represents the public IP address of the virtual machine. All three IP addresses are passed to `configuration` and `start` handlers as environment variables using the following formats:

- `CONTAINER_IP`: the IP address of the container. It should be used for binding purposes.
- `CLOUD_IP`: the IP address of the virtual machine running the container. This IP is probably cloud provider-specific and cannot be reached from outside the cloud.
- `PUBLIC_IP`: the public IP address of the virtual machine running the container, if available.

Port Numbers in the Execution Environment. Moreover, the port numbers used within the container do not necessarily match the port numbers used by the operating system hosting the Docker container. Indeed, the Executionware will not force the use of any fixed port numbers outside the container in order to allow maximum flexibility. Again, the port numbers are passed to the `configuration` and `start` handlers as environment variables. The name of the variable is based on the name of the provided `communication` from the deployment model. For instance, the provided port `ExpManPort` from Listing 6.1 is mapped to the following three environment variables:

- `CONTAINER_EXPMANPORT`: the port number as specified in the deployment model and as accessible from within the container. Should be used for binding.

¹⁶<http://docker.io>

- `CLOUD_EXPMANPORT`: the port number as accessible from within the cloud.
- `PUBLIC_EXPMANPORT`: the port number as accessible from the outside world (*i.e.*, by using the public IP).

Outgoing Connections in the Execution Environment. Similar to the provided communications, there is a mapping for required communications. The main difference is that it uses sets of IP addresses in combination with ports. For instance, the required port `StoManPortReq` from Listing 6.1 is mapped to the following three environment variables; all consisting of a sequence of `ipv4:port` separated by a comma (,).

- `PUBLIC_STOMANPORTREQ`: provides access to the public IP addresses and public ports of all downstream component instances.
`<stoman1publicip>:<public_port>,<stoman2publicip>:<public_port>`
- `CLOUD_STOMANPORTREQ`: provides access to the cloud-internal IP addresses and cloud-internal ports of all downstream component instances. Note that the addresses of component instances that are not hosted in the same cloud as the local component instances are still in the list, but it is very likely that traffic cannot be routed to them.
`<stoman1cloudip>:<cloud_port>,<stoman2cloudip>:<cloud_port>`
- `CONTAINER_STOMANPORTREQ`: provides access to the container-internal IP addresses and container-internal ports of all downstream component instances. Note that the addresses of component instances that are not hosted in the same container as the local component instances are still in the list, but it is very likely that traffic cannot be routed to them.
`<stoman1containerip>:<container_port>,<stoman2containerip>:<container_port>`

Currently, it is up to the CAMEL user to decide which of the combinations is needed. Using the public IPs and ports enables a full routability of network traffic, but may introduce networking overhead. Future work may improve upon this status quo by providing the shortest distance combinations of the addresses.

Updating Required Communications. Whenever the set of downstream instances changes (*e.g.*, a new Storage Manager instance is created), the start handler of the associated required communication is invoked. This should lead to an updated configuration and if necessary a re-started main process.

The Start Life Cycle Scripts. The life cycle script attached to start is a special script. It is supposed to not return from its call. As such, the Execution Environment will use `exec <install command from CAMEL>`. This means that the CAMEL user **shall not** use more than one command in the install handler, as *e.g.*, `cd directory && ./run.sh` will not work. The same holds for `cd directory ; ./run.sh`. Use `directory/run.sh` instead.

Other Environment Variables. Per default, Docker uses only very few environment variables in a default container, except for `HOME` (home of the current user—`root` by default), `PWD` (current working directory—`/` by default), and `PATH`. Users should not rely on any of these.

6.1.2 Life Cycle Scripts for Windows-based Applications

For Windows-based deployments the Executionware relies on the same deployment model as GNU/Linux deployments, mainly the configuration block of internal components. All handlers are executed as a single Powershell script. The return value will be interpreted and a value different from `0` will move the instance to an error state. Information about ports, connection and the local host is provided via environment variables.

Like on GNU/Linux, the different handlers are not necessarily executed in the very same shell instance, in particular the same Powershell instance. If custom environment variables are set in a handler which will be used in a later handler they have to be set on the user-level. In Powershell this can be achieved with the command `[Environment]::SetEnvironmentVariable($NAME, $VALUE, "User")`. `$NAME` and `$VALUE` represent the respective parameters and the static value "User" specifies the user-level for the environment variable. For Windows deployments every component runs in its own folder. All commands are executed as Administrator and no other existing users can be assumed. If further users are required, the handlers are responsible for creating them. The networking is discussed in the following.

IP Addresses in the Execution Environment. Unlike Unix components, Windows components have at least one IP address. Depending on the cloud provider, it is possible that this IP is a cloud-internal IP and there is a second IP address that represents the public IP address of the virtual machine. Both IP addresses are passed to configuration and start handlers as environment variables:

- `CLOUD_IP`: the IP address of the virtual machine running the component. This IP is probably cloud provider-specific and cannot be reached from outside the cloud.

- `PUBLIC_IP`: the public IP address of the virtual machine running the component, if available.

Port Numbers in the Execution Environment. As Windows components just run in a unique folder and not in a container like Unix components there is a small difference. The port numbers of Windows components match the port numbers of the virtual machine's operating system. The port numbers are passed to the configuration and start handlers as environment variables. The name of the variable is based on the name of the provided communication from the deployment model. Considering the example from Listing 6.1 as a Windows component the resulting two environment variables are set:

- `CLOUD_EXPMANPORT`: the port number as accessible from within the cloud.
- `PUBLIC_EXPMANPORT`: the port number as accessible from the outside world (*i.e.*, by using the public IP).

Outgoing Connections in the Execution Environment. The mapping of required communications is similar to Unix components (*cf.* Section 6.1.1) except there is no need to map the communication to a container-internal IP. Again, consider Listing 6.1 as a Windows component the required port is mapped to the following environment variables:

- `PUBLIC_STOMANPORTREQ`: provides access to the public IP addresses and public ports of all downstream component instances.
`<stoman1publicip>:<public_port>,<stoman2publicip>:<public_port>`
- `CLOUD_STOMANPORTREQ`: provides access to the cloud-internal IP addresses and cloud-internal ports of all downstream component instances. Note that addresses of component instances not hosted in the same cloud as the local component instance are still in the list, but very likely cannot be routed to.
`<stoman1cloudip>:<cloud_port>,<stoman2cloudip>:<cloud_port>`

Updating Required Communications. Whenever the set of downstream instances changes (*e.g.*, a new Storage Manager instance is created), the start handler of the associated required communication is invoked. This should lead to an updated configuration and if necessary a re-started main process.

The Start Life Cycle Scripts. In contrast to Unix components, for Windows components the start command is supposed to return from its call. It is also possible to use more than one command like in all other handlers.

Other Environment Variables. The default Windows environment variables are set (*e.g.*, `HOME` or `ProgramData`), but the user should be aware that the environment variables can differ depending on the operating system version.

7 Requirements

The requirement package of the CAMEL metamodel is not based on existing DSLs and has been developed to enable the specification of requirements for cross-cloud applications. A requirement can be *hard*, such as a service level objective (SLO) (*e.g.*, response time < 100 ms), meaning that it is measurable and must be satisfied, or *soft*, such as an optimisation objective (*e.g.*, maximise performance), meaning that it is not measurable. A soft requirement has a *priority* from 0.0 to 1.0 that is used to rank these requirements when reasoning on the application and generating a new CPSM. In the following, we exemplify the main concepts in the requirement package.

Assume that we have to specify the requirements for the components of the Scalarm use case. Listing 7.1 shows this specification in textual syntax.

```
quantitative hardware CoreIntensive specifies that a virtual machine must
have from 8 to 32 CPU cores and from 4 to 8 GB of RAM. os Ubuntu spec-
ifies that a virtual machine must run Ubuntu operating system 64-bit edition.
location requirement NorwayReq specifies that a virtual machine must be de-
ployed in Norway. locations refers to the location NO in the location model
ScalarmLocation (cf. Listing 13.1). The three requirements above are referred to
by the requirement set CoreIntensiveUbuntuNorwayRS in the deployment model
ScalarmDeployment (cf. Listing 6.2).
```

```
slo CPUMetricSLO specifies that the metric condition CPUMetricCondition is
an SLO. service level refers to the metric condition CPUMetricCondition in the
metric model ScalarmModel (cf. Listing 8.2).
```

```
optimisation requirement MinimisePerformanceDegradationOfExperimentMan-
ager specifies that the metric MeanValueOfResponseTimeOfAllExperimentManagers-
Metric of the component ExperimentManager should be minimised and that this
minimisation has a priority 0.8. metric refers to the metric MeanValueOfResponse-
TimeOfAllExperimentManagersMetric in the metric model ScalarmModel (cf. List-
ing 8.2), while component refers to the internal component ExperimentManager in
the deployment model ScalarmDeployment (cf. Listing 6.2). optimisation require-
ment MinimiseDataFarmingExperimentMakespan specifies a similar optimisation re-
quirement with priority 0.2.
```

```
group ScalarmRequirementGroup specifies that the requirements CPUMetricSLO,
MinimisePerformanceDegradationOfExperimentManager, and MinimiseDataFarming-
ExperimentMakespan are logically connected through the AND operator. Note that
```


a requirement group also allows a requirement tree to be created. For example, a top-level requirement group could contain two or more requirement groups logically connected by an OR operator. Each of the latter requirement groups could in turn contain single requirements, such as SLOs, logically connected by an AND operator.

horizontal scale requirement `HorizontalScaleSimulationManager` specifies that the component `SimulationManager` can scale horizontally between 1 and 5 instances. `component` refers to the internal component `SimulationManager` in the deployment model `ScalarmDeployment` (cf. Listing 6.2).

Listing 7.1: Scalarm requirement model

```

1 requirement model ScalarmRequirement {
2
3   quantitative hardware CoreIntensive {
4     core: 8..32
5     ram: 4096..8192
6   }
7
8   os Ubuntu {
9     os: 'Ubuntu' 64os
10  }
11
12  location requirement NorwayReq {
13    locations [ScalarmLocation.NO]
14  }
15
16  slo CPUMetricSLO {
17    service level: ScalarmModel.ScalarmMetric.CPUMetricCondition
18  }
19
20  optimisation requirement
21  MinimisePerformanceDegradationOfExperimentManager {
22    function: MIN
23    metric: ScalarmModel.ScalarmMetric.
24    MeanValueOfResponseTimeOfAllExprimentManagersMetric
25    component: ScalarmModel.ScalarmDeployment.ExperimentManager
26    priority: 0.8
27  }
28
29  optimisation requirement MinimiseDataFarmingExperimentMakespan {
30    function: MIN
31    metric: ScalarmModel.ScalarmMetric.MakespanMetric
32    component: ScalarmModel.ScalarmDeployment.ExperimentManager
33    priority: 0.2
34  }
35
36  group ScalarmRequirementGroup {
37    operator: AND
38    requirements [ScalarmRequirement.CPUMetricSLO, ScalarmRequirement.
39    MinimisePerformanceDegradationOfExperimentManager,
40    ScalarmRequirement.MinimiseDataFarmingExperimentMakespan]
41  }
42
43  horizontal scale requirement HorizontalScaleSimulationManager {

```

```

40     component: ScalarmModel.ScalarmDeployment.SimulationManager
41     instances: 1 .. 5
42   }
43 }

```

8 Metrics and Scalability Rules

The scalability and metric packages of the CAMEL metamodel are based on the Scalability Rule Language (SRL) [18, 8]. SRL enables the specification of rules that support complex adaptation scenarios of cross-cloud applications. In particular, SRL provides mechanisms for specifying cross-cloud behaviour patterns, metric aggregations, and the scaling actions to be enacted in order to change the provisioning and deployment of an application. SRL is inspired by the Esper Processing Language (EPL)¹⁷ with respect to the specification of event patterns with formulas including logic operators and timing. SRL provides mechanisms for (a) specifying event patterns, (b) specifying scaling actions, and (c) associating these scaling actions with the corresponding event patterns. Moreover, in order to identify event patterns, the components of cross-cloud applications must be monitored. Therefore, SRL provides mechanisms for (d) expressing which components must be monitored by which metrics, and (e) associating event patterns with monitoring data. In the following, we exemplify the main concepts in the scalability and metric packages.

Assume that we have to specify scalability rules and metrics for the Scalarm use case. The SimulationManager scales out when the following conditions are met: (a) all instances have had an average CPU load beyond 50% for at least 5 *min*, and (b) concurrently at least one instance has had an average CPU load beyond 80% for at least 1 *min*. These conditions are represented by the following expression, where cpu_i and cpu_j represent the average CPU loads for instance i and j , respectively:

$$\forall i \mid cpu_i \geq 50 \wedge \exists j \mid cpu_j \geq 80$$

To implement this scenario, we specified a scalability and a metric model that represent, respectively: (a) the scalability rule along with the events used to trigger it, and (b) the metrics and conditions that, when evaluated, trigger the action of the scalability rule.

Listing 8.1 shows the scalability model in textual syntax. `non-functional event CPUAvgMetricNFEAll` specifies the violation of a metric condition. `metric`

¹⁷<http://esper.codehaus.org/>

condition refers to the metric condition `CPUAvgMetricConditionAll` in the metric model `ScalarmMetric` (cf. Listing 8.2). non-functional event `CPUAvgMetricNFEAny` specifies a similar violation of a metric condition.

binary event pattern `CPUAvgMetricBEPAnd` specifies that the non-functional events above are logically connected through an AND operator.

horizontal scaling action `HorizontalScalingSimulationManager` specifies a scale-out action. `vm` and `internal` component refer to the `vm` `CPUIntensiveUbuntuNorway` and the `internal` component `SimulationManager`, respectively, in the deployment model `ScalarmDeployment` (cf. Listings 6.2 and 6.1).

scalability rule `CPUScalabilityRule` refers to the binary event pattern and the horizontal scaling action above, along with the scale requirement `HorizontalScaleSimulationManager` in the requirement model `ScalarmRequirement` (cf. Listing 7.1).

Listing 8.1: Scalarm scalability model

```

1 scalability model ScalarmScalability {
2
3   non-functional event CPUAvgMetricNFEAll {
4     metric condition: ScalarmModel.ScalarmMetric.
      CPUAvgMetricConditionAll
5     violation
6   }
7
8   non-functional event CPUAvgMetricNFEAny {
9     metric condition: ScalarmModel.ScalarmMetric.
      CPUAvgMetricConditionAny
10    violation
11  }
12
13  binary event pattern CPUAvgMetricBEPAnd {
14    left event: ScalarmModel.ScalarmScalability.CPUAvgMetricNFEAll
15    right event: ScalarmModel.ScalarmScalability.CPUAvgMetricNFEAny
16    operator: AND
17  }
18
19  horizontal scaling action HorizontalScalingSimulationManager {
20    type: SCALE_OUT
21    vm: ScalarmModel.ScalarmDeployment.CPUIntensiveUbuntuNorway
22    internal component: ScalarmModel.ScalarmDeployment.
      SimulationManager
23  }
24
25  scalability rule CPUScalabilityRule {
26    event: ScalarmModel.ScalarmScalability.CPUAvgMetricBEPAnd
27    actions [ScalarmModel.ScalarmScalability.
      HorizontalScalingSimulationManager]
28    scale requirements [ScalarmRequirement.
      HorizontalScaleSimulationManager]
29  }
30 }

```

Listing 8.2 shows the metric model in textual syntax. raw metric `CPUmetric`, along with the elements referred by it, specify a raw (sensor) metric measuring CPU load. composite metric `CPUAverage`, along with the elements referred by it, specify an average CPU load metric. composite metric context `CPUAvgMetricContextAll` and composite metric context `CPUAvgMetricContextAny` specify that the average CPU load metric is instantiated in two contexts, one with a window of five minutes and one with a window of one minute, respectively. The aggregated composite metrics are instantiated as metric instances twice per virtual machine, and once per metric context.

Listing 8.2: Scalarm metric model

```

1 metric model ScalarmMetric {
2
3   window Win5Min {
4     window type: SLIDING
5     size type: TIME_ONLY
6     time size: 5
7     unit: ScalarmModel.ScalarmUnit.minutes
8   }
9
10  window Win1Min {
11    window type: SLIDING
12    size type: TIME_ONLY
13    time size: 1
14    unit: ScalarmModel.ScalarmUnit.minutes
15  }
16
17  schedule Schedule1Min {
18    type: FIXED_RATE
19    interval: 1
20    unit: ScalarmModel.ScalarmUnit.minutes
21  }
22
23  schedule Schedule1Sec {
24    type: FIXED_RATE
25    interval: 1
26    unit: ScalarmModel.ScalarmUnit.seconds
27  }
28
29  sensor CPUSensor {
30    configuration: 'cpu_usage;de.uniulm.omi.cloudiator.visor.sensors.
31    CpuUsageSensor'
32    push
33  }
34
35  property CPUProperty {
36    type: MEASURABLE
37    sensors [ScalarmMetric.CPUSensor]
38  }
39
40  raw metric CPUmetric {
41    value direction: 0
42    layer: IaaS
43    property: ScalarmModel.ScalarmMetric.CPUProperty

```

```

43     unit: ScalarmModel.ScalarmUnit.CPUUnit
44     value type: ScalarmModel.ScalarmType.Range0_100
45 }
46
47 raw metric context CPURawMetricContext {
48     metric: ScalarmModel.ScalarmMetric.CPUMetric
49     sensor: ScalarmMetric.CPUSensor
50     component: ScalarmModel.ScalarmDeployment.SimulationManager
51     schedule: ScalarmModel.ScalarmMetric.Schedule1Sec
52     quantifier: ALL
53 }
54
55 raw metric context CPUMetricConditionContext {
56     metric: ScalarmModel.ScalarmMetric.CPUMetric
57     sensor: ScalarmMetric.CPUSensor
58     component: ScalarmModel.ScalarmDeployment.SimulationManager
59     quantifier: ANY
60 }
61
62 composite metric CPUAverage {
63     description: "Average of the CPU"
64     value direction: 1
65     layer: PaaS
66     property: ScalarmModel.ScalarmMetric.CPUProperty
67     unit: ScalarmModel.ScalarmUnit.CPUUnit
68
69     metric formula FormulaAverage {
70         function arity: UNARY
71         function pattern: MAP
72         MEAN( ScalarmModel.ScalarmMetric.CPUMetric )
73     }
74 }
75
76 composite metric context CPUAvgMetricContextAll {
77     metric: ScalarmModel.ScalarmMetric.CPUAverage
78     component: ScalarmModel.ScalarmDeployment.SimulationManager
79     window: ScalarmModel.ScalarmMetric.Win5Min
80     schedule: ScalarmModel.ScalarmMetric.Schedule1Min
81     composing metric contexts [ScalarmModel.ScalarmMetric.
82     CPURawMetricContext]
83     quantifier: ALL
84 }
85
86 composite metric context CPUAvgMetricContextAny {
87     metric: ScalarmModel.ScalarmMetric.CPUAverage
88     component: ScalarmModel.ScalarmDeployment.SimulationManager
89     window: ScalarmModel.ScalarmMetric.Win1Min
90     schedule: ScalarmModel.ScalarmMetric.Schedule1Min
91     composing metric contexts [ScalarmModel.ScalarmMetric.
92     CPURawMetricContext]
93     quantifier: ANY
94 }
95
96 metric condition CPUMetricCondition {
97     context: ScalarmModel.ScalarmMetric.CPUMetricConditionContext
98     threshold: 80.0
99     comparison operator: >

```

```

100  metric condition CPUAvgMetricConditionAll {
101      context: ScalarmModel.ScalarmMetric.CPUAvgMetricContextAll
102      threshold: 50.0
103      comparison operator: >
104  }
105
106  metric condition CPUAvgMetricConditionAny {
107      context: ScalarmModel.ScalarmMetric.CPUAvgMetricContextAny
108      threshold: 80.0
109      comparison operator: >
110  }
111 }

```

8.1 Interplay with Executionware

In order to enact the scalability rules, the Executionware provides a monitoring and adaptation engine for cross-cloud applications. In PaaSage, this monitoring and adaptation engine is Axe [9]. In particular, the Executionware configures the monitoring probes based on the specified metrics and evaluates the specified scalability rules. If a metric condition is violated, the Executionware enacts the specified scaling action (*e.g.*, scale-out), which may include the provisioning of vm instances, the deployment of component instances, and the wiring of these (see Section 6.1). Life-cycle handlers attached to the specified communications can wire existing component instances by reconfiguring them. The interested reader may refer to [9] for a detailed description of how the Executionware enacts scaling actions.

9 Organisations

The organisation package of the CAMEL metamodel is based on the organisation subset of CERIF [17]. CERIF is an EU standard¹⁸ for research information. In particular, the organisation package of the CAMEL reuses the concepts from CERIF for specifying organisations, users, and roles. In the following, we exemplify the main concepts in the organisation package.

Assume that we have to specify the organisation model for the Scalarm use case. Listing 9.1 shows this specification in textual syntax.

organisation AGH specifies the organisation AGH (Akademia Górniczo-Hutnicza, *i.e.*, AGH University of Science and Technology), while user MichalOrzechowski specifies the user Michal Orzechowski belonging to the organisation AGH and owning the application Scalarm (*cf.* Listing 5.1).

¹⁸<http://cordis.europa.eu/cerif/>

role `devop` specifies the role *development and operations* (`devop`), while role assignment `MichalOrzechowskiDevop` specifies the assignment of the role `devop` to the user Michal Orzechowski, which is valid from 1 March 2016 to 28 February 2017.

Listing 9.1: Scalarm organisation model

```
1 organisation model AGHOrganisation {
2
3   organisation AGH {
4     www: 'http://www.agh.edu.pl/en/'
5     email: 'info@agh.edu.pl'
6   }
7
8   user MichalOrzechowski {
9     first name: Michal
10    last name: Orzechowski
11    email: 'morzech@agh.edu.pl'
12    password: '*****'
13  }
14
15  role devop
16
17  role assignment MichalOrzechowskiDevop {
18    start: 2016-03-01
19    end: 2017-02-28
20    assigned on: 2016-02-29
21    user: AGHOrganisation.morzech
22    role: ScalarmModel.AGHOrganisation.devop
23  }
24 }
```

10 Providers

The provider package of the CAMEL metamodel is based on Saloon [30, 31, 32]. Saloon is a tool-supported DSL for specifying the features of cloud providers and matching them with requirements by leveraging feature models [3] and ontologies [16]. In the following, we exemplify the main concepts in the provider package.

Assume that we have to specify the provider model for the Scalarm use case. Listing 10.1 shows an excerpt of the provider model for a SINTEF private cloud specified using the CAMEL textual syntax.

root feature `SINTEF` is the root feature and specifies the attributes and sub-features characterising `SINTEF`'s private cloud. attribute `DeliveryModel` specifies that `SINTEF` provides a private cloud. attribute `ServiceModel` specifies that `SINTEF` provides a IaaS. attribute `Availability` specifies that the guaranteed availability of `SINTEF`'s private cloud is 95%. attribute `Driver` specifies

that the provider uses an OpenStack Nova API. attribute `EndPoint` specifies the endpoint of the SINTEF's OpenStack Nova API.

feature `VM` is a sub-feature and specifies the attributes characterising the virtual machine flavours provided by SINTEF's private cloud, such as type (attribute `VMType`), operating system (attribute `VMOS`), size of RAM (attribute `VM-Memory`), size of storage (attribute `VMStorage`), and number of CPU cores (attribute `VMCores`). Each attribute has a value type, and a unit type. For instance, `VMMemory` has `MemoryList`, a list of integer values (256, 512, 2048, etc.), as value type, and `MEGABYTES` as unit type (*cf.* Listings 15.1 and 14.1). feature cardinality specifies that the feature has a cardinality between 1 and 8.

constraints specifies the constraints characterising SINTEF's private cloud. `implies M1LARGEMapping` is an intra-feature constraint and specifies the mapping between the assigned resources and the virtual machine flavours provided by SINTEF's private cloud. For instance, the first attribute constraint specifies that the size of RAM of the `m1.LARGE` virtual machine flavour is 8192 (megabytes).

Listing 10.1: SINTEF provider model (excerpt)

```
1 provider model SINTEFProvider {
2
3   root feature SINTEF {
4
5     attributes {
6
7       attribute DeliveryModel {
8         value: string value 'Private'
9         value type: ScalarmModel.SINTEFType.StringValueType
10      }
11
12      attribute ServiceModel {
13        value: string value 'IaaS'
14        value type: ScalarmModel.SINTEFType.StringValueType
15      }
16
17      attribute Availability {
18        unit type: PERCENTAGE
19        value: string value '95'
20        value type: ScalarmModel.SINTEFType.StringValueType
21      }
22
23      attribute Driver {
24        value: string value 'openstack-nova'
25        value type: ScalarmModel.SINTEFType.StringValueType
26      }
27
28      attribute EndPoint {
29        value: string value 'https://minicloud.modelbased.net'
30        value type: ScalarmModel.SINTEFType.StringValueType
31      }
32    }
33  }
```



```

34     sub-features {
35
36         feature VM {
37
38             attributes {
39                 attribute VMType {value type: ScalarmModel.SINTEFType.
VMTypeEnum}
40                 attribute VMOS {value type: ScalarmModel.SINTEFType.VMOSEnum
}
41                 attribute VMMemory {unit type: MEGABYTES value type:
ScalarmModel.SINTEFType.MemoryList}
42                 attribute VMStorage {unit type: GIGABYTES value type:
ScalarmModel.SINTEFType.StorageList}
43                 attribute VMCores {value type: ScalarmModel.SINTEFType.
CoresList}
44             }
45
46             feature cardinality {cardinality: 1 .. 8}
47         }
48     ...
49 }
50
51     feature cardinality {cardinality: 1 .. 1}
52 }
53
54     constraints {
55     ...
56     implies M1LARGEMapping {
57
58         from: ScalarmModel.SINTEFProvider.SINTEF.VM
59         to: ScalarmModel.SINTEFProvider.SINTEF.VM
60
61         attribute constraints {
62
63             attribute constraint {
64                 from: ScalarmModel.SINTEFProvider.SINTEF.VM.VMType
65                 to: ScalarmModel.SINTEFProvider.SINTEF.VM.VMMemory
66                 from value: string value 'M1.LARGE'
67                 to value: int value 8192
68             }
69
70             attribute constraint {
71                 from: ScalarmModel.SINTEFProvider.SINTEF.VM.VMType
72                 to: ScalarmModel.SINTEFProvider.SINTEF.VM.VMCores
73                 from value: string value 'M1.LARGE'
74                 to value: int value 4
75             }
76
77             attribute constraint {
78                 from: ScalarmModel.SINTEFProvider.SINTEF.VM.VMType
79                 to: ScalarmModel.SINTEFProvider.SINTEF.VM.VMStorage
80                 from value: string value 'M1.LARGE'
81                 to value: int value 80
82             }
83         }
84     }
85     ...
86 }
87 }

```

11 Security

The security package of the CAMEL metamodel is not based on existing DSLs and has been developed to enable the specification of security aspects of cross-cloud applications. It enables the specification of high-level and low-level security requirements and capabilities that can be exploited for filtering providers as well as adapting cross-cloud applications. In the following, we exemplify the main concepts in the security package.

Assume that we have to specify the security model for the Scalarm use case. Listing 9.1 shows this specification in textual syntax.

`domain IAM` specifies the domain of Identity & Access Management (IAM). `domain IAM_CLCPM` and `IAM_UAR` specify two sub-domains of IAM, namely Credential Life Cycle/Provision Management (CLCPM) and User Access Revocation (UAR), respectively.

`property IdentityAssurance` specifies an abstract property of identity assurance associated with the domain IAM. `security control IAM_02` specifies a security control associated with the sub-domain (CLCPM) and the property `IdentityAssurance`. Similarly, `security control IAM_11` specifies a security control associated with the sub-domain (UAR) and the property `IdentityAssurance`. Note that these security controls are part of the set of security controls identified by the Cloud Security Alliance (CSA).¹⁹

`security capability SecCap` specifies a security capability associated with the security controls `IAM_02` and `IAM_11`. Finally, the organisation model `AmazonExt` refers to the security capability `SecCap`, which specifies that the Amazon provider supports this security capability.

Listing 11.1: Scalarm security model

```
1 security model ScalarmSecurity {
2
3   domain IAM {
4     name: "Identity & Access Management"
5     sub-domains [ScalarmSecurity.IAM_CLCPM, ScalarmSecurity.IAM_CLCPM]
6   }
7
8   domain IAM_CLCPM {
9     name: "Credential Life Cycle/Provision Management"
10  }
11
12  domain IAM_UAR {
13    name: "User Access Revocation"
14  }
```

¹⁹<https://cloudsecurityalliance.org/>

```

15
16 property IdentityAssurance {
17     description: "The ability of a relying party to determine, with
18         some level of certainty, that a claim to a particular identity made
19         by some entity can be trusted to actually be the claimant's true,
20         accurate and correct identity."
21     type: ABSTRACT
22     domain: ScalarmSecurity.IAM
23 }
24
25 security control IAM_02 {
26     specification: "User access policies and procedures shall be
27         established, and supporting business processes and technical
28         measures implemented, for ensuring appropriate identity,
29         entitlement, and access management for all internal corporate and
30         customer (tenant) users with access to data and organisationally-
31         owned or managed (physical and virtual) application interfaces and
32         infrastructure network and systems components."
33     domain: ScalarmSecurity.IAM
34     sub-domain: ScalarmSecurity.IAM_CLCPM
35     security properties [ScalarmModel.ScalarmSecurity.
36         IdentityAssurance]
37 }
38
39 security control IAM_11 {
40     specification: "Timely de-provisioning (revocation or modification
41         ) of user access to data and organisationally-owned or managed (
42         physical and virtual) applications, infrastructure systems, and
43         network components, shall be implemented as per established
44         policies and procedures and based on user's change in status (e.g.,
45         termination of employment or other business relationship, job
46         change or transfer). Upon request, provider shall inform customer (
47         tenant) of these changes, especially if customer (tenant) data is
48         used as part the service and/or customer (tenant) has some shared
49         responsibility over implementation of control."
50     domain: ScalarmSecurity.IAM
51     sub-domain: ScalarmSecurity.IAM_UAR
52     security properties [ScalarmModel.ScalarmSecurity.
53         IdentityAssurance]
54 }
55
56 security capability SecCap {
57     controls [ScalarmSecurity.IAM_02, ScalarmSecurity.IAM_11]
58 }
59 }
60
61 requirement model ScalarmExtendedReqModel {
62
63     security requirement AllIAMsSupported {
64         controls [ScalarmSecurity.IAM_02, ScalarmSecurity.IAM_11]
65     }
66 }
67
68 organisation model AmazonExt {
69
70     provider Amazon {
71         www: 'https://aws.amazon.com/'
72         email: 'contact@amazon.com'
73         PaaS

```

```

54     IaaS
55     security capability [ScalarmModel.ScalarmSecurity.SecCap]
56   }
57 }

```

12 Execution

The execution package of the CAMEL metamodel is not based on existing DSLs and has been developed to enable the recording of historical data about the execution of cross-cloud applications. Historical data, such as metric measurements and SLO assessments, can be used for auditing purposes as well as for optimising the CAMEL model to better exploit the available cloud infrastructures [20]. In PaaSage, the execution model is automatically manipulated by the PaaSage platform during the execution phase (see Section 2), and so it should be in the general case too. In the following, we exemplify the main concepts in the execution package.

Assume that we have to record the execution of the Scalarm use case. Listing 12.1 shows this specification in textual syntax.

`vm binding ScalarmVMBinding` specifies that the virtual machine instance `CoreIntensiveUbuntuNorwayInst` (*cf.* Listing 6.5) is bound to the execution context `EC1`.

`raw metric instance CPUMetricInstance` specifies that the metric instance `CPUMetricInstance` is an instance of the metric `CPUMetric` and is bound to the virtual machine instance `CoreIntensiveUbuntuNorwayInst` and the execution context `EC1` (*cf.* Listing 6.5).

`execution context EC1` specifies the current execution context. It refers to the application being executed, the deployment model of the application, the requirement group that led to this deployment model, and an indication of the total cost of application execution along with a reference to the corresponding monetary unit (*cf.* Listing 14.1).

`vm measurement VM1` specifies the virtual machine measurement for the CPU metric instance. It refers to the execution context, the metric instance, the virtual machine instance (*cf.* Listing 6.5), the measured value (`95.0`), and the timestamp of the measurement.

Similar to the `vm measurement`, the `assessment A1` specifies the assessment for the CPU metric SLO. It comprises the appropriate reference, the indication that the SLO has been violated, and the timestamp of the assessment.

Listing 12.1: Scalarm execution model

```

1 metric model ScalarmMetric {
2

```

```

3  vm binding ScalarmVMBinding {
4      execution context: ScalarmExecution.EC1
5      vm instance: ScalarmModel.ScalarmDeployment.
        CoreIntensiveUbuntuNorwayInst
6  }
7
8  raw metric instance CPUMetricInstance {
9      metric: ScalarmModel.ScalarmMetric.CPUMetric
10     sensor: ScalarmMetric.CPUSensor
11     binding: ScalarmModel.ScalarmMetric.ScalarmVMBinding
12 }
13 }
14
15 execution model ScalarmExecution {
16
17     execution context EC1 {
18         application: ScalarmModel.ScalarmApplication
19         deployment model: ScalarmModel.ScalarmDeployment
20         requirement group: ScalarmRequirement.ScalarmRequirementGroup
21         total cost: 100.0
22         cost unit: ScalarmModel.ScalarmUnits.Euro
23     }
24
25     vm measurement VM1 {
26         execution context: ScalarmExecution.EC1
27         metric instance: ScalarmMetric.RawCPUMetricInstance
28         vm instance: ScalarmModel.ScalarmDeployment.
                CoreIntensiveUbuntuNorwayInst
29         value: 95.0
30         time: 2016-10-31 T 22:50
31     }
32
33     assessment A1 {
34         execution context: ScalarmExecution.EC1
35         measurement: ScalarmExecution.VM1
36         slo: ScalarmRequirement.CPUMetricSLO
37         violated
38         time: 2016-10-31 T 22:50
39     }
40 }

```

13 Locations

The location package of the CAMEL metamodel is not based on existing DSLs and has been developed to enable the specification of locations. A location can be a *geographical region* (e.g., Europe) or a *cloud location* (e.g., Amazon EC2 eu-west-1). A geographical region can refer to a parent region, which allows for the creation of hierarchies of geographical regions (e.g., continent, sub-continent, and country). Similar to the geographical region, a cloud location can refer to a parent location. In the following, we exemplify the main concepts in the location package.

Assume that we have to specify the locations for the Scalarm use case. Listing 13.1 shows this specification in textual syntax.

region EU specifies the region Europe. country NO and country DE specifies the countries Norway and Germany, respectively. parent regions refers to the parent region Europe. The location Norway is referred to by the location requirement NorwayReq in the requirement model ScalarmRequirement (*cf.* Listing 7.1).

Listing 13.1: Scalarm location model

```
1 location model ScalarmLocation {
2
3   region EU {
4     name: 'Europe'
5   }
6
7   country NO {
8     name: 'Norway'
9     parent regions [ScalarmLocation.EU]
10  }
11
12  country DE {
13    name: 'Germany'
14    parent regions [ScalarmLocation.EU]
15  }
16 }
```

14 Units

The unit package of the CAMEL metamodel is not based on existing DSLs and has been developed to enable the specification of units that are adopted by the following packages: (a) metric, where they are used to define the unit of measurement for a metric, (b) execution, where they are used to define the monetary unit for the cost of a particular application execution, and (c) the provider, where they are used to define the unit for a particular feature attribute. In the following, we exemplify the main concepts in the unit package.

Assume that we have to specify the units of the Scalarm use case. Listing 14.1 shows this specification in textual syntax.

The unit model ScalarmUnit encompasses seven units that are referred to by metrics in the metric model ScalarmMetric (*cf.* Listing 8.2). The specification of each unit follows the pattern: <unit_class> <unit_name>: <unit_type>. For instance, monetary unit {Euro: EUROS} specifies a monetary unit named “euros” and typed EUROS).

Listing 14.1: Scalarm unit model

```
1 unit model ScalarmUnit {
2   monetary unit {Euro: EUROS}
3   throughput unit {SimulationsPerSecondUnit: TRANSACTIONS_PER_SECOND}
```

```

4  time interval unit {ResponseTimeUnit: MILLISECONDS}
5  time interval unit {ExperimentMakespanInSecondsUnit: SECONDS}
6  transaction unit {NumberOfSimulationsLeftInExperimentUnit:
    TRANSACTIONS}
7  dimensionless {AvailabilityUnit: PERCENTAGE}
8  dimensionless {CPUUnit: PERCENTAGE}
9  }

```

The complete list of available units is as follows:

- `core` unit, which represents the unit of CPU cores
- `monetary` unit, which represents a monetary unit (*e.g.*, EUROS)
- `request` unit, which represents the unit of number requests
- `storage` unit, which represents the unit of storage (*e.g.*, BYTES)
- `throughput` unit, which represents the unit of throughput (*e.g.*, REQUESTS-
_PER_SECOND)
- `time interval` unit, which represents the unit of time interval (*e.g.*, SE-
CONDS)
- `transaction` unit, which represents the number of transactions
- `dimensionless`, which represents a unit without dimension (*e.g.*, a unit of
PERCENTAGE is dimensionless)

15 Types

The type package of the CAMEL metamodel is also based on Saloon [30, 31, 32]. It provides the concepts to specify value types and values used across CAMEL models (*e.g.*, integer, string, or enumeration). In the following, we exemplify the main concepts in the type package.

Assume that we have to specify the types of the Scalarm use case. Listing 15.1 shows this specification in textual syntax.

`range Range0_100` specifies an integer range between 0 and 99 (*i.e.*, 100, not included). It is referred to by the metric `CPUmetric` (*cf.* Listing 8.2).

`range Range0_1000` specifies an integer range between 1 (*i.e.*, 0, not included) and 1000. It is referred to by the metric `ResponseTimeMetric` (*cf.* Listing 8.2).

`range DoubleRange0_100` specifies a double range between 0.0 and 100.0. It is referred to by the metric `AvailabilityMetric` (*cf.* Listing 8.2).

The other value types, enumerations, and lists in the type model SINTEFType are referred to by the features in the provider model SINTEFProvider Availability-Metric (*cf.* Listing 10.1).

Listing 15.1: Scalarm type model

```
1 type model ScalarmType {
2
3   range Range0_100 {
4     primitive type: IntType
5     lower limit {int value 0 included}
6     upper limit {int value 100}
7   }
8
9   range Range0_10000 {
10    primitive type: IntType
11    lower limit {int value 0}
12    upper limit {int value 10000 included}
13  }
14
15  range DoubleRange0_100 {
16    primitive type: DoubleType
17    lower limit {double value 0.0 included}
18    upper limit {double value 100.0 included}
19  }
20 }
21
22 type model SINTEFType {
23
24   string value type StringValueType {
25     primitive type: StringType
26   }
27
28   enumeration VMTypeEnum {
29     values [ 'M1.MICRO' : 0, ..., 'M1.LARGE' : 4, ..., 'C1.XXLARGE' :
30             15 ]
31   }
32
33   enumeration VMOSEnum {
34     values [ 'Fedora 20 server x86_64' : 0, 'Ubuntu 14.04 LTS Server
35             x86_64' : 1, ... ]
36   }
37
38   list StorageList {
39     values [ int value 0, int value 20, int value 40, int value 80,
40             int value 160 ]
41   }
42
43   list MemoryList {
44     values [ int value 256, int value 512, int value 2048, int value
45             4096, int value 8192, int value 16384, int value 32768 ]
46   }
47
48   list CoresList {
49     values [ int value 1, int value 2, int value 4, int value 8, int
50             value 16 ]
51   }
52 }
```


16 Java APIs and CDO

As mentioned, CAMEL consists of an Ecore model (*cf.* Section 5). This enables to specify CAMEL models using the CAMEL Textual Editor as well as to programmatically manipulate and persist them through Java APIs.

Listing 16.1 shows the creation of a VM of Scalarm (*cf.* Section 2). The classes that are instantiated and initialised in the code have been automatically generated by the EMF generator model based on the deployment package. All class instances are obtained using the DeploymentFactory object specific for the deployment package. This object provides a set of methods that are used to make sure the model objects are appropriately instantiated.

Listing 16.1: A sample VM definition

```
//create a ML VM
VM coreIntensiveVM = DeploymentFactory.eINSTANCE.createVM();
//First create VM requirement set & add it to the deployment model
VMRequirementSet coreIntensiveReqs = DeploymentFactory.eINSTANCE.
    createVMRequirementSet();
mlReqs.setName("CoreIntensiveReqs");
coreIntensiveVM.setVmRequirementSet(coreIntensiveReqs);
sensAppDeploymentModel.getVmRequirementSets().add(coreIntensiveReqs);
//Create a quantitative hardware requirement to include it in the
    requirement set
QuantitativeHardwareRequirement coreIntensiveRequirment =
    RequirementFactory.eINSTANCE.createQuantitativeHardwareRequirement
    ();
coreIntensiveRequirment.setName("CoreIntensive");
coreIntensiveRequirment.setMaxCores(32);
coreIntensiveRequirment.setMinCores(8);
coreIntensiveRequirment.setMaxRAM(8192);
coreIntensiveRequirment.setMinRAM(4096);
rm.getRequirements().add(coreIntensiveRequirment);
coreIntensiveReqs.setQuantitativeHardwareRequirement(
    coreIntensiveRequirment);
//Create a L0cation requirement imposing that the VM should be located
    in Scotland
LocationRequirement germanyRequirement = RequirementFactory.eINSTANCE.
    createLocationRequirement();
germanyRequirement.setName("GermanyReq");
germanyRequirement.getLocations().add(ScalarmLocationModel.germany);
rm.getRequirements().add(germanyRequirement);
coreIntensiveReqs.setLocationRequirement(germanyRequirement);
//Fix other details of the VM including its name and provided host
coreIntensiveVM.setName("CoreIntensiveVM");

ProvidedHost vmMLProv = DeploymentFactory.eINSTANCE.createProvidedHost
    ();
vmMLProv.setName("VMMLProv");

ml.getProvidedHosts().add(vmMLProv);
//Finally add the VM to the deployment model
scalarmDeploymentModel.getVms().add(ml);
```

Listing 16.2 shows the specification of Scalarm's ExperimentManager Internal-Component. This internal component has an associated Configuration, which specifies the corresponding life cycle control scripts (e.g., download and install commands). It also specifies communications with other internal components by creating corresponding RequiredCommunication, ProvidedCommunication entities and a dedicated type of host RequiredHost that the ExperimentManager requires.

Listing 16.2: A sample InternalComponent definition

```
//create a Scalarm InternalComponent give it a name
InternalComponent experimentManagerIc = DeploymentFactory.eINSTANCE.
    createInternalComponent();

//Associate it with a particular configuration
Configuration experimentManagerCompResourceConf = DeploymentFactory.
    eINSTANCE.createConfiguration();
experimentManagerCompResourceConf.setDownloadCommand("wget_https://
    github.com/kliput/scalarm_service_scripts/archive/paasage.tar.gz&&
    sudo_apt-get_update&&sudo_apt-get_install_y_groovy_ant&&tar_-
    zxvf_paasage.tar.gz&&cd_scalarm_service_scripts-paasage");
experimentManagerCompResourceConf.setInstallCommand("cd_
    scalarm_service_scripts-paasage&&./experiment_manager_install.sh"
    );
experimentManagerCompResourceConf.setStartCommand("cd_
    scalarm_service_scripts-paasage&&./experiment_manager_start.sh");
experimentManagerIc.getConfigurations().add(
    experimentManagerCompResourceConf);

//Create a provided communication element on port 443
ProvidedCommunication experimentManagerProvidedCommunication =
    DeploymentFactory.eINSTANCE.createProvidedCommunication();
experimentManagerProvidedCommunication.setName("ExperimentManager");
experimentManagerProvidedCommunication.setPortNumber(443);
experimentManagerIc.getProvidedCommunications().add(
    experimentManagerProvidedCommunication);

//Create a required communication with Scalarm StorageManager
component
RequiredCommunication experimentManagerReqStorageCommunication =
    DeploymentFactory.eINSTANCE.createRequiredCommunication();
experimentManagerReqStorageCommunication.setIsMandatory(true);
experimentManagerReqStorageCommunication.setName("
    ExperimentManager_consumes_SotrageManager");
experimentManagerReqStorageCommunication.setPortNumber(20001);
experimentManagerIc.getRequiredCommunications().add(
    experimentManagerReqStorageCommunication);

//Create a required host element
RequiredHost coreIntensiveUbuntuGermanyHostReq = DeploymentFactory.
    eINSTANCE.createRequiredHost();
coreIntensiveUbuntuGermanyHostReq.setName("
    coreIntensiveUbuntuGermanyHostReq");
experimentManagerIc.setRequiredHost(coreIntensiveUbuntuGermanyHostReq)
    ;

//Finally add the component to the deployment model
scalarmDeploymentModel.getInternalComponents().add(experimentManagerIc
```

```
);
```

Listing 16.3 shows the creation of a `Communication` binding between the Scalarm's `ExperimentManager` and the Scalarm's `StorageManager`.

Listing 16.3: A sample `Communication` definition

```
//Create communication by also specifying its name and the provided
and required communications
Communication experimentManagerToStorageManager = DeploymentFactory.
eINSTANCE.createCommunication();
experimentManagerToStorageManager.setName("
experimentManagerToStorageManager");
experimentManagerToStorageManager.setProvidedCommunication(
storageManagerProvidedCommunicationMongodNginx);
experimentManagerToStorageManager.setRequiredCommunication(
experimentManagerReqStorageCommunication);

//Add communication to deployment model
scalarmDeploymentModel.getCommunications().add(
experimentManagerToStorageManager);
```

Listing 16.4 shows the specification of a `Hosting` binding between the `ExperimentManager` `InternalComponent` and the VM of `coreIntensiveUbuntuGermanyHost` type.

Listing 16.4: A sample `Hosting` definition

```
//Create hosting, specify its name and the required and provided hosts
Hosting experimentManagerToCoreIntensiveUbuntuGermany =
DeploymentFactory.eINSTANCE.createHosting();
experimentManagerToCoreIntensiveUbuntuGermany.setName("
ExperimentManagerToCoreIntensiveUbuntuGermany");
experimentManagerToCoreIntensiveUbuntuGermany.setProvidedHost(
coreIntensiveUbuntuGermanyHost);
experimentManagerToCoreIntensiveUbuntuGermany.setRequiredHost(
coreIntensiveUbuntuGermanyHostReq);

//Add hosting to the deployment model
scalarmDeploymentModel.getHostings().add(
experimentManagerToCoreIntensiveUbuntuGermany);
```

Listing 16.5 shows the process of saving a deployment model in a CDO repository. As mentioned, CDO uses a set of APIs that are designed after the JDBC APIs. In order to save a model, we first need to create a session and obtain a transaction over it. This example adopts a local database that is accessed using a TCP connector from the `Net4j` framework²⁰, a partner project used within CDO. Once the transaction is obtained, the deployment model refers to the `CDOResource` responsible for its persistence, and the transaction is committed.

Listing 16.5: Saving a deployment model in a CDO repository

²⁰<https://www.eclipse.org/modeling/emf/?project=net4j>

```

//initialize and activate a container
final IManagedContainer container = ContainerUtil.createContainer();
Net4jUtil.prepareContainer(container);
TCPUtil.prepareContainer(container);
// CDONet4jUtil.prepareContainer(container);
container.activate();

// create a Net4j TCP connector
final IConnector connector = (IConnector) TCPUtil.getConnector(
    container, "localhost:2036");

// create the session configuration
CDONet4jSessionConfiguration config = CDONet4jUtil.
    createNet4jSessionConfiguration();
config.setConnector(connector);
config.setRepositoryName("repo1");

// create the actual session with the repository
CDONet4jSession cdoSession = config.openNet4jSession();

// obtain a transaction object
CDOTransaction transaction = cdoSession.openTransaction();

// create a CDO resource object
CDOResource resource = transaction.getOrCreateResource("/
    scalarmResource1");
EObject camelModel = ScalarmModel.createScalarmModel();

// associate the deployment model to the resource
resource.getContents().add(camelModel);

// commit the transaction to persist the model
transaction.commit();

```

Listing 16.6 shows the process of loading and modifying a deployment model. In this example, the host VM for the ExperimentManager is changed. We change it by setting the ProvidedHost of the Hosting to point to a virtual machine definition suitable for single CPU intensive tasks (assuming it is initially one suited for multi-core processing).

Listing 16.6: Loading and modifying a deployment model in a CDO repository

```

// open a new transaction
CDOTransaction transaction = cdoSession.openTransaction();

// load the existing resource of SensApp and get the top-most model
// which is a deployment one
CDOResource resource = transaction.getResource("/scalarmResource1");
assertTrue(resource.getContents().get(0) instanceof DeploymentModel);
DeploymentModel model = (DeploymentModel) resource.getContents().get
    (0);

// get provided host for the CPU intensive virtual machine (which we
// want to change to)
ProvidedHost CPUIntensiveProvidedHost = null;
for(VM vm: model.getVMs()){
    if (vm.getName().equals("CPUIntensiveUbuntuGermany")){

```

```

        CPUIntensiveProvidedHost = vm.getProvidedHost();
        break;
    }
}

// find the current hosting in the deployment model
Hosting currentHosting = null;
for (Hosting h2: model.getHostings()){
    if (h2.getName().equals("
        ExperimentManagerToCoreIntensiveUbuntuGermany")){
        currentHosting = h2;
        break;
    }
}

// modify hosting in the deployment model and replace the current
// provided host (which is presumably "CoreIntensiveUbuntuGermany")
currentHosting.setName("ExperimentManagerToCPUIntensiveUbuntuGermany")
;
currentHosting.setProvidedHost(CPUIntensiveProvidedHost);

// commit the transaction to persist the updated model
transaction.commit();

```

The example above show the Java code for programmatically saving, loading, and modifying part of a deployment model in a CDO repository. The Java code for programmatically saving, loading, and modifying models from other packages of the CAMEL metamodel is analogous. The full version of the Java code of the Scalarm example is available for reference in the Git repository at OW2.²¹

17 Related Work

In the following, we compare CAMEL with related work. We distinguish between tools (*e.g.*, DevOps and cloud orchestration tools) to automate the deployment of cloud applications and languages to model cloud aspects. For the latter category, we define six comparison criteria and evaluate the languages according to these criteria. This comparison will validate our claim that CAMEL advances the state-of-the-art in modelling and execution of cloud applications.

²¹https://github.com/groundnutty/scalarm-paasage-camel/tree/master/model_in_java/src/main/java/eu/paasage/camel/agh

17.1 Tools

In the cloud community, libraries such as `jclouds`²² or `DeltaCloud`²³ provide generic APIs abstracting over the heterogeneous APIs of IaaS providers. These libraries reduce the cost and effort of deploying cloud applications and can be used by the platforms supporting CAMEL. For instance, the PaaS platform uses `jclouds`.

DevOps tools such as `Puppet`²⁴ or `Chef`²⁵ rely on scripting languages to specify the deployment of cloud applications. These tools increase the automation in deploying cloud applications. However, the deployment scripts cannot be treated as deployment models, which introduces a mismatch between the deployment topology of cloud applications and the technique used to represent them.

Cloud orchestration tools such as `Cloudify`²⁶ or `Apache Brooklyn`²⁷ rely on the TOSCA [29] (see below) to specify the topologies of cloud applications along with the processes for their orchestration. These tools facilitate the provisioning, deployment, and monitoring of cloud applications across multiple cloud infrastructures [2]. However, TOSCA does not provide an instance model and hence does not support models@run-time, which makes these tools unsuitable for reasoning on the models and hence enabling self-adaptive cross-cloud applications.

17.2 Languages

In the research community, within the Reservoir²⁸ EU project, Galán et al. [14] proposed a service specification language for cloud computing platforms, which extends the DMTF's Open Virtualization Format (OVF) standard to address the specific requirements of these environments.

Within the 4CaaS²⁹ EU project, Nguyen et al. [24] proposed a language to specify Blueprint Templates—a uniform abstract description for cloud service offerings that may cross different cloud computing layers, *i.e.*, infrastructure and platform.

²²<http://www.jclouds.org>

²³<http://deltacloud.apache.org/>

²⁴<https://puppetlabs.com/>

²⁵<http://www.opscode.com/chef/>

²⁶<http://getcloudify.org/>

²⁷<https://brooklyn.apache.org/>

²⁸<http://www.reservoir-fp7.eu/>

²⁹<http://www.4caast.eu>

The MODAClouds project³⁰ provides a family of DSLs collectively called MODACloudML. MODACloudML relies on the following three layers of abstraction: (i) the *cloud-enabled computation independent model* (CCIM) to describe an application and its data, (ii) the CPIM (as in PaaSage) to describe concerns of cloud applications in a cloud-agnostic way, and (iii) the CPSM (as in PaaSage) to describe concerns of cloud applications in a cloud-specific way, so that they can be provisioned and deployed on specific clouds.

The ARTIST project³¹ provides the Cloud Application Modelling Language (CAML). CAML consists of an *internal* DSL [13] realised as a UML library along with UML profiles [4] rather than an *external* DSL such as CAMEL. The main rationale behind the latter stems from the goal of the ARTIST project to support the migration of existing applications to the cloud, whereby UML models are reverse-engineered and tailored to a selected cloud environment.

The ARCADIA project³² provides a methodology and a framework to support the development of highly-distributed applications (HDAs) that are reconfigurable by design. The ARCADIA Framework [34] relies on unikernel technology in order to bundle microservices, and leverages on an extensible *context model* throughout the entire life cycle of HDAs. Similar to CAMEL, the ARCADIA Context Model [15] has multiple facets, such as the component model, the service graph model, the service deployment model, and the service run-time model.

In the standards community, the Topology and Orchestration Specification for Cloud Applications (TOSCA) [29] is a specification developed by the OASIS consortium, which provides a language for specifying the components comprising the topology of cloud applications along with the processes for their orchestration.

17.3 Comparison

In the following, we define six comparison criteria and evaluate the aforementioned languages according to these criteria. These criteria were selected to evaluate the usefulness, usability, and self-adaptation support of the languages. In particular, the abstract syntax and aspect coverage, delivery model support, and models@run-time support reflect the usefulness of the language; the concrete syntax and integration level reflect the usability; and models@run-time support also reflects the self-adaptation support.

³⁰<http://www.modaclouds.eu/>

³¹<http://www.artist-project.eu/>

³²<http://www.arcadia-framework.eu>

Abstract syntax. The abstract syntax of a language describes the set of concepts, their attributes, and their relations, as well as the rules for combining these concepts to specify valid statements that conform to this abstract syntax. The abstract syntax can be defined using formalisms that provide different capabilities. For instance, XML Schema are more suitable for tree-based structures, while MOF-based formalisms are more suitable for graph-based structures and offer better tool support and better integration with constraint languages such as OCL. This criterion is used to identify which formalisms are used by a language. The values for this criterion are “XML Schema” and “MOF”.³³

Concrete syntax. The concrete syntax of a language describes the textual or graphical notation that renders the concepts of the abstract syntax, their attributes, and their relations. The concrete syntax can be defined using notations that provide a trade-off between the intuitiveness and the effectiveness of the syntax. For instance, a textual syntax may be less intuitive but more effective than a corresponding graphical syntax. This criterion is used to identify which notations are supported by a language. The values for this criterion can be “XML”, “txt” (textual), and “gra” (graphical).

Aspect coverage. A language may cover multiple aspects within the same domain or across multiple domains. For instance, in CAMEL we specify the life cycle of cross-cloud applications using 11 aspects, namely deployment, requirement, location, metric, scalability, provider, organisation, security, execution, unit, and type. This criterion reflects how many of these aspects are covered by a language. The values for this criterion can be “low” if it covers at most three aspects, “medium” if it covers at most six aspects, and “high” otherwise.

Integration level. A language that covers multiple aspects may provide different levels of integration across these aspects, especially when these aspects include similar or equivalent concepts. The integration solution has to: (a) join equivalent concepts and separate similar concepts into respective sub-concepts; (b) homogenise the remaining concepts so that they are defined at the same level of granularity; (c) enforce a uniform formalism and notation for the abstract and concrete syntaxes; and (d) enforce the consistency, correctness, and integrity of the models. Each of these steps is a precondition to the following step and requires an increasing amount of effort. This criterion reflects how many of these steps have been adopted to integrate the sub-languages. The values for this criterion can be “low” if the sub-languages were integrated following only step (a), “medium” if they were integrated following steps (a) and (b), “high” if they

³³Abstract syntaxes defined in Ecore fall into this category.

were integrated following all steps, and “N/A” if they were not integrated. In the last case, each sub-language covers one aspect and is independent from the other sub-languages. This independence leads to the following disadvantages: (a) it raises the complexity of the language, since each sub-language has its own abstract and concrete syntax; (b) it steepens the learning curve and increases the modelling effort for the same reason; (d) it leads to the duplication of modelling for similar or equivalent concepts; (e) it leads to the manual validation of cross-aspect dependencies.

Delivery model support. A cross-cloud application may exploit any of the cloud delivery models, namely IaaS and PaaS. A language for specifying the life cycle of cross-cloud applications should support concepts for each of these cloud delivery models. This criterion reflects how many of these delivery models are supported by a language. The values for this criterion can be “IaaS” and “PaaS”.

Models@run-time support. Models@run-time [5] provides an abstract representation of the underlying running system, whereby a modification to the model is enacted on-demand in the system, and a change in the system is automatically reflected in the model. Models@run-time can be implemented using the type-instance pattern [1], which facilitates reusability and abstraction. For instance, we implemented the type-instance pattern in two aspects, namely deployment and metric. In the case of deployment, this allows to automatically adapt the component- and virtual machine instances in the deployment model based on scalability rules (*e.g.*, scale out a Scalarm service along with the underlying virtual machine). In the case of monitoring, this allows to automatically populate the metric model with metric instances (*e.g.*, CPU load measurements of the virtual machine hosting the Scalarm service). This criterion reflects how many of these aspects implement the type-instance pattern. The values for this criterion can be “deployment” and “metric”.

17.4 Analysis

Table 1 shows the comparison of the languages based on the criteria above. CAMEL scores best in all criteria apart from the last one.

Compared to CAMEL, the Reservoir OVF Extension and the 4CaaS Blueprint Templates do not cover the multiple aspects necessary for modelling and especially executing cross-cloud applications.

MODACloudML and CAMEL achieve similar goals, but with different approaches: MODACloudML is a family of loosely coupled DSLs, while CAMEL is a standalone language. CAMEL has the advantage of providing a uniform

Language	Abstract Syntax	Concrete Syntax	Aspect Coverage	Integration Level	Delivery Model Support	Models@run-time Support
Reservoir OVF Extension	XML Schema	XML	low	N/A	IaaS	N/A
4CaaS Blueprint Template	XML Schema	XML	low	N/A	IaaS, PaaS	N/A
ModaCloudML	MOF	XML, gra, txt	medium	low	IaaS, PaaS	deployment
CAML	MOF	gra	medium	medium	IaaS	N/A
ARCADIA Context Model	XML Schema	XML	high	medium	IaaS	deployment
TOSCA	XML Schema	XML, txt	medium	medium	IaaS, PaaS	N/A
CAMEL	MOF	XML, gra, txt	high	high	IaaS	deployment, metric

Table 1: The cloud language comparison table

abstract and concrete syntax, which resulted from a process of coupling and homogenising multiple DSLs [25]. However, ModaCloudML supports both IaaS and PaaS while CAML only supports the former. CAML will be extended to include support PaaS in future work.

CAML achieves a subset of the goals of CAMEL. CAML does not support aspects of execution, while CAMEL provides full support for models@run-time.

The ARCADIA Context Model is less expressive than CAMEL with respect to specifying complex conditions on composite metrics. However, the ARCADIA Context Model is more expressive than CAMEL with respect to specifying adaptation actions, and provides concepts for specifying unikerel and microservices aspects. CAMEL could possibly be extended to support these aspects.

TOSCA supports the specification of types and templates, but not instances, in deployment models. CAMEL, in contrast, supports the specification of types, templates, and instances. Note that CAMEL provides built-in types such as vm, internal component, communication, and hosting, while TOSCA offers similar types in a library of reusable types and allows to define arbitrary types. In its current form, TOSCA can only be used at design-time, while CAMEL can be used at both design-time and run-time.

As part of the joint standardisation effort of MODAClouds, PaaSage, and ARCADIA, SINTEF presented the models@run-time approach to the TOSCA technical committee (TC) and proposed to form an ad hoc group to investigate how TOSCA could be extended to support this approach. The TC welcomed this proposal and approved the formation of the Instance Model Ad Hoc group in October 2015. The group is currently co-led by Alessandro Rossini from SINTEF and Derek Palma from Vnomic. The work performed in this group will guarantee that the contribution of CAMEL will partly be integrated into the

standard.

18 Conclusion and Future Work

CAMEL allows to specify multiple aspects of cross-cloud applications, such as provisioning, deployment, service level, monitoring, scalability, providers, organisations, users, roles, security, and execution. It supports models@run-time, which enables reasoning on CAMEL models and hence managing self-adaptive cross-cloud applications.

In this document, we described the design and implementation of CAMEL. Moreover, we provided a real-world running example to illustrate how to specify models in a concrete textual syntax and how to programmatically manipulate and persist them through Java APIs.

In the future, we will continue to develop CAMEL iteratively. In particular, we will adapt and extend the capabilities of CAMEL to the changing requirements. In this respect, the developers will provide feedback on whether the concepts in CAMEL are adequate to design and implement their components. Similarly, the users will provide feedback on whether the concepts in CAMEL are satisfactory for modelling the use cases. In addition to the PaaSage project, CAMEL has been adopted by the CACTOS³⁴, CloudSocket³⁵, and MUSA³⁶ projects. This will guarantee the further development and validation of CAMEL in a wide variety of cloud computing scenarios.

In addition, CAMEL models that conform to an old version of CAMEL often have to be migrated to conform to its current version. In the future, we would like to integrate a solution for the challenge of maintaining multiple versions and automatically migrating CAMEL models [25] based on CDO and Edapt.

Finally, we will contribute to the Instance Model Ad Hoc group of TOSCA so that the contribution of CAMEL will partly be integrated into the standard.

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³⁴<http://www.cactosfp7.eu/>

³⁵<https://www.cloudsocket.eu>

³⁶<http://www.musa-project.eu/>

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References

- [1] Colin Atkinson and Thomas Kühne. ‘Rearchitecting the UML infrastructure’. In: *ACM Transactions on Modeling and Computer Simulation* 12.4 (2002), pp. 290–321. doi: 10.1145/643120.643123.
- [2] Daniel Baur, Daniel Seybold, Frank Griesinger, Athanasios Tsitsipas, Christopher B. Hauser and Jörg Domaschka. ‘Cloud Orchestration Features: Are Tools Fit for Purpose?’ In: *UCC 2015: 8th IEEE/ACM International Conference on Utility and Cloud Computing*. Ed. by Ioan Raicu, Omer F. Rana and Rajkumar Buyya. IEEE Computer Society, 2015, pp. 95–101. ISBN: 978-0-7695-5697-0. doi: 10.1109/UCC.2015.25.
- [3] David Benavides, Sergio Segura and Antonio Ruiz Cortés. ‘Automated analysis of feature models 20 years later: A literature review’. In: *Inf. Syst.* 35.6 (2010), pp. 615–636. doi: 10.1016/j.is.2010.01.001.
- [4] Alexander Bergmayr, Javier Troya, Patrick Neubauer, Manuel Wimmer and Gerti Kappel. ‘UML-based Cloud Application Modeling with Libraries, Profiles, and Templates’. In: *CloudMDE 2014: 2nd International Workshop on Model-Driven Engineering on and for the Cloud*. Ed. by Richard F. Paige, Jordi Cabot, Marco Brambilla, Louis M. Rose and James H. Hill. Vol. 1242. CEUR Workshop Proceedings. CEUR, 2014, pp. 56–65. URL: <http://ceur-ws.org/Vol-1242/paper7.pdf>.
- [5] Gordon S. Blair, Nelly Bencomo and Robert B. France. ‘Models@run.time’. In: *IEEE Computer* 42.10 (2009), pp. 22–27. doi: 10.1109/MC.2009.326.
- [6] Jörg Domaschka, Daniel Baur, Daniel Seybold and Frank Griesinger. ‘Cloudiator: A Cross-Cloud, Multi-Tenant Deployment and Runtime Engine’. In: *SummerSOC 2015: 9th Workshop and Summer School On Service-Oriented Computing 2015*. 2015.
- [7] Jörg Domaschka, Frank Griesinger, Daniel Baur and Alessandro Rossini. ‘Beyond Mere Application Structure: Thoughts on the Future of Cloud Orchestration Tools’. In: *Procedia Computer Science* 68 (2015). Cloud Forward 2015: 1st International Conference on Cloud Forward: From Distributed to Complete Computing, pp. 151–162. ISSN: 1877-0509. doi: 10.1016/j.procs.2015.09.231.

- [8] Jörg Domaschka, Kyriakos Kritikos and Alessandro Rossini. ‘Towards a Generic Language for Scalability Rules’. In: *Advances in Service-Oriented and Cloud Computing—Workshops of ES OCC 2014*. Ed. by Guadalupe Ortiz and Cuong Tran. Vol. 508. Communications in Computer and Information Science. Springer, 2015, pp. 206–220. ISBN: 978-3-319-14885-4. DOI: 10.1007/978-3-319-14886-1_19.
- [9] Jörg Domaschka, Daniel Seybold, Frank Griesinger and Daniel Baur. ‘Axe: A Novel Approach for Generic, Flexible, and Comprehensive Monitoring and Adaptation of Cross-Cloud Applications’. In: *Advances in Service-Oriented and Cloud Computing—Workshops of ES OCC 2015*. Ed. by Antonio Celesti and Philipp Leitner. Vol. 567. Communications in Computer and Information Science. Springer, 2016, pp. 184–196. ISBN: 978-3-319-33312-0. DOI: 10.1007/978-3-319-33313-7_14.
- [10] Nicolas Ferry, Franck Chauvel, Alessandro Rossini, Brice Morin and Arnor Solberg. ‘Managing multi-cloud systems with CloudMF’. In: *NordiCloud 2013: 2nd Nordic Symposium on Cloud Computing and Internet Technologies*. Ed. by Arnor Solberg, Muhammad Ali Babar, Marlon Dumas and Carlos E. Cuesta. ACM, 2013, pp. 38–45. ISBN: 978-1-4503-2307-9. DOI: 10.1145/2513534.2513542.
- [11] Nicolas Ferry, Alessandro Rossini, Franck Chauvel, Brice Morin and Arnor Solberg. ‘Towards model-driven provisioning, deployment, monitoring, and adaptation of multi-cloud systems’. In: *CLOUD 2013: 6th IEEE International Conference on Cloud Computing*. Ed. by Lisa O’Conner. IEEE Computer Society, 2013, pp. 887–894. ISBN: 978-0-7695-5028-2. DOI: 10.1109/CLOUD.2013.133.
- [12] Nicolas Ferry, Hui Song, Alessandro Rossini, Franck Chauvel and Arnor Solberg. ‘CloudMF: Applying MDE to Tame the Complexity of Managing Multi-Cloud Applications’. In: *UCC 2014: 7th IEEE/ACM International Conference on Utility and Cloud Computing*. Ed. by Randall Bilof. IEEE Computer Society, 2014, pp. 269–277. DOI: 10.1109/UCC.2014.36.
- [13] Martin Fowler. *Domain-Specific Languages*. Addison-Wesley Professional, 2010. ISBN: 978-0321712943.
- [14] Fermín Galán, Américo Sampaio, Luis Roderó-Merino, Irit Loy, Victor Gil and Luis Miguel Vaquero. ‘Service specification in cloud environments based on extensions to open standards’. In: *COMSWARE 2009: 4th International Conference on COMMunication System softWARE and MiddlewaRE*. Ed. by Jan Bosch and Siobhán Clarke. ACM, 2009, 19:1–19:12. ISBN: 978-1-60558-353-2. DOI: 10.1145/1621890.1621915.

- [15] Panagiotis Gouvas et al. *D2.2—Definition of the ARCADIA Context Model*. ARCADIA project deliverable. July 2015.
- [16] Thomas R. Gruber. ‘A translation approach to portable ontology specifications’. In: *Knowledge Acquisition* 5.2 (June 1993), pp. 199–220. ISSN: 1042-8143. DOI: 10.1006/knac.1993.1008.
- [17] Keith Jeffery, Nikos Houssos, Brigitte Jörg and Anne Asserson. ‘Research information management: the CERIF approach’. In: *IJMSO* 9.1 (2014), pp. 5–14. DOI: 10.1504/IJMSO.2014.059142.
- [18] Kyriakos Kritikos, Jörg Domaschka and Alessandro Rossini. ‘SRL: A Scalability Rule Language for Multi-Cloud Environments’. In: *CloudCom 2014: 6th IEEE International Conference on Cloud Computing Technology and Science*. Ed. by Juan E. Guerrero. IEEE Computer Society, 2014, pp. 1–9. ISBN: 978-1-4799-4093-6. DOI: 10.1109/CloudCom.2014.170.
- [19] Kyriakos Kritikos, Tom Kirkham, Bartosz Kryza and Philippe Massonet. ‘Security Enforcement for Multi-Cloud Platforms—The Case of PaaSage’. In: *Procedia Computer Science* 68 (2015). Cloud Forward 2015: 1st International Conference on Cloud Forward: From Distributed to Complete Computing, pp. 103–115. ISSN: 1877-0509. DOI: 10.1016/j.procs.2015.09.227.
- [20] Kyriakos Kritikos, Kostas Magoutis and Dimitris Plexousakis. ‘Towards Knowledge-Based Assisted IaaS Selection’. In: *CloudCom 2016: 8th IEEE International Conference on Cloud Computing Technology and Science*. IEEE Computer Society, 2016.
- [21] Dariusz Król and Jacek Kitowski. ‘Self-scalable services in service oriented software for cost-effective data farming’. In: *Future Generation Comp. Syst.* 54 (2016), pp. 1–15. DOI: 10.1016/j.future.2015.07.003.
- [22] Thomas Kühne. ‘Matters of (meta-)modeling’. In: *Software and Systems Modeling* 5.4 (2006), pp. 369–385. DOI: 10.1007/s10270-006-0017-9.
- [23] Peter Mell and Timothy Grance. *The NIST Definition of Cloud Computing*. Special Publication 800-145. National Institute of Standards and Technology, Sept. 2011.
- [24] Dinh Khoa Nguyen, Francesco Lelli, Yehia Taher, Michael Parkin, Mike P. Papazoglou and Willem-Jan van den Heuvel. ‘Blueprint Template Support for Engineering Cloud-Based Services’. In: *ServiceWave 2011: 4th European Conference Towards a Service-Based Internet*. Ed. by Witold Abramowicz, Ignacio Martín Llorente, Mike SurrIDGE, Andrea Zisman and Julien Vayssière. Vol. 6994. Lecture Notes in Computer Science. Springer,

2011, pp. 26–37. ISBN: 978-3-642-24754-5. DOI: 10.1007/978-3-642-24755-2_3.

- [25] Nikolay Nikolov, Alessandro Rossini and Kyriakos Kritikos. ‘Integration of DSLs and Migration of Models: A Case Study in the Cloud Computing Domain’. In: *Procedia Computer Science* 68 (2015). Cloud Forward 2015: 1st International Conference on Cloud Forward: From Distributed to Complete Computing, pp. 53–66. ISSN: 1877-0509. DOI: 10.1016/j.procs.2015.09.223.
- [26] Object Management Group. *Object Constraint Language*. 2.4. <http://www.omg.org/spec/OCL/2.4/>. Feb. 2014.
- [27] Object Management Group. *Unified Modeling Language Specification*. 2.4.1. <http://www.omg.org/spec/UML/2.4.1/>. Aug. 2011.
- [28] Object Management Group. *XML Metadata Interchange Specification*. 2.4.2. <http://www.omg.org/spec/XMI/2.4.2/>. Apr. 2014.
- [29] Derek Palma and Thomas Spatzier. *Topology and Orchestration Specification for Cloud Applications (TOSCA)*. Tech. rep. Organization for the Advancement of Structured Information Standards (OASIS), June 2013. URL: <http://docs.oasis-open.org/tosca/TOSCA/v1.0/cos01/TOSCA-v1.0-cos01.pdf>.
- [30] Clément Quinton, Nicolas Haderer, Romain Rouvoy and Laurence Duchien. ‘Towards multi-cloud configurations using feature models and ontologies’. In: *MultiCloud 2013: International Workshop on Multi-cloud Applications and Federated Clouds*. ACM, 2013, pp. 21–26. ISBN: 978-1-4503-2050-4. DOI: 10.1145/2462326.2462332.
- [31] Clément Quinton, Daniel Romero and Laurence Duchien. ‘Cardinality-based feature models with constraints: a pragmatic approach’. In: *SPLC 2013: 17th International Software Product Line Conference*. Ed. by Tomoji Kishi, Stan Jarzabek and Stefania Gnesi. ACM, 2013, pp. 162–166. ISBN: 978-1-4503-1968-3. DOI: 10.1145/2491627.2491638.
- [32] Clément Quinton, Romain Rouvoy and Laurence Duchien. ‘Leveraging Feature Models to Configure Virtual Appliances’. In: *CloudCP 2012: 2nd International Workshop on Cloud Computing Platforms*. ACM, 2012, pp. 21–26. ISBN: 978-1-4503-1161-8. DOI: 10.1145/2168697.2168699.
- [33] Alessandro Rossini. ‘Cloud Application Modelling and Execution Language (CAMEL) and the PaaSage Workflow’. In: *Advances in Service-Oriented and Cloud Computing—Workshops of ESOC 2015*. Ed. by Antonio Celesti and Philipp Leitner. Vol. 567. Communications in Computer

and Information Science. Springer, 2016, pp. 437–439. ISBN: 978-3-319-33313-7. DOI: 10.1007/978-3-319-33313-7.

- [34] Alessandro Rossini, Franck Chauvel, Panagiotis Gouvas, Anastasios Zafeiropoulos, Costantinos Vassilakis and Eleni Fotopoulou. *D3.1a—Smart Controller Reference Implementation*. ARCADIA project deliverable. Apr. 2016.
- [35] Alessandro Rossini, Kiriakos Kritikos, Nikolay Nikolov, Jörg Domaschka, Frank Griesinger, Daniel Seybold and Daniel Romero. *D2.1.3—CAMEL Documentation*. PaaSage project deliverable. Oct. 2015.
- [36] Alessandro Rossini, Adrian Rutle, Yngve Lamo and Uwe Wolter. ‘A formalisation of the copy-modify-merge approach to version control in MDE’. In: *Journal of Logic and Algebraic Programming* 79.7 (2010), pp. 636–658. DOI: 10.1016/j.jlap.2009.10.003.