RESEARCH ARTICLE

Component-aware Orchestration of Cloud-based Enterprise Applications, from TOSCA to Docker and Kubernetes

Matteo Bogo | Jacopo Soldani* | Davide Neri | Antonio Brogi

Department of Computer Science, University of Pisa, Pisa, Italy

Correspondence

*Jacopo Soldani, c/o Dipartimento di Informatica, Università di Pisa, Largo B. Pontecorvo 3, 56127, Pisa, Italia. Email: soldani@di.unipi.it

Summary

Enterprise IT is currently facing the challenge of coordinating the management of complex, multi-component applications across heterogeneous cloud platforms. Containers and container orchestrators provide a valuable solution to deploy multicomponent applications over cloud platforms, by coupling the lifecycle of each application component to that of its hosting container. We hereby propose a solution for going beyond such a coupling, based on the OASIS standard TOSCA and on Docker. We indeed propose a novel approach for deploying multi-component applications on top of existing container orchestrators, which allows to manage each component independently from the container used to run it. We also present prototype tools implementing our approach, and we show how we effectively exploited them to carry out a concrete case study.

KEYWORDS:

application orchestration, cloud, Docker, TOSCA

1 | INTRODUCTION

Cloud computing is a flexible, cost-effective and proven delivery platform for running on-demand distributed applications¹. To fully exploit the potentials of cloud computing and facilitate the scalability, reliability and portability of applications, various cloud-native architectural styles have emerged (with microservices being one of the most prominent examples). This has resulted in a growth of the complexity of applications, which nowadays integrate dozens (if not hundreds) of interacting components². The problem of automating the deployment and management of such complex, multi-component applications over heterogeneous cloud platforms has hence become one of the main challenges in enterprise IT^{3,4}.

The components forming an application are typically deployed on cloud platforms by relying on virtualisation technologies. Container-based virtualisation⁵ is getting more and more momentum in this scenario, as it provides an isolated and lightweight virtual runtime environment⁶. Docker (https://www.docker.com) constitutes the *de-facto* standard for container-based virtualisation, and it permits packaging software components (together with all software dependencies they need to run) in Docker images, which are then exploited as read-only templates to create and run Docker containers. Container orchestrators are then used to automate the deployment and management of containerised applications at a large scale. Docker Swarm (https://docs.docker.com/engine/swarm) and Kubernetes (https://kubernetes.io) are currently the most popular solutions for orchestrating Docker containers, providing all necessary abstractions for scaling, discovering, load-balancing and interconnecting Docker containers over single and multi-host systems^{7,8}.

Docker containers are however treated as a sort of "black-boxes", since they constitute the minimal entity that can be orchestrated. Container orchestrators can indeed create, start, stop and delete containers, but they do not provide support for coordinating the management of the components running within containers. The lifecycle of the software components forming a containerised application is hence tightly coupled to that of their hosting containers. For instance, when the orchestrator creates and starts a container, all the software components it contains have to be created and started as well, as the orchestrator does not provide a support for creating or starting them afterwards. The same holds when containers are stopped or deleted, as the components they are hosting get stopped and deleted as well. This is because currently existing container orchestrators do not provide a support for coordinating the management of software components independently from that of their hosting containers⁹.

Decoupling the management of application components from that of the containers hosting them can anyway bring various advantages. For instance, this allows to employ Docker containers as so-called *system containers*, i.e., a lightweight portable alternative to virtual machines¹⁰. It also enables inter-process communication within the components running in the same container, without requiring them to necessarily communicate over the network¹¹. This helps saving resources, thus containing costs or enabling a fine-grained orchestration on infrastructures where computing and networking resources are costly and limited, e.g., in edge clusters¹². Other known advantages of decoupling application components from their hosting containers are maintainability and reuse¹³. Deployment requirements of multi-component applications change over time. If components are coupled to their hosting containers, this requires to re-package them from scratch whenever their deployment requirements change.

Following this idea, we hereafter propose a solution for managing the software components forming an application independently from the containers used to run them. The proposed solution is intended to allow a more flexible, component-aware management of multi-component applications on top of existing Docker-based container orchestrators, and it does so by relying on the OASIS standard TOSCA for specifying and orchestrating multi-component applications. More precisely, starting from an existing representation of multi-component applications in TOSCA (taken from our previous work⁹), we provide the following contributions:

- We propose a novel approach for managing the lifecycle of software components forming a multi-component application independently from that of the containers used to host such components.
- We present the prototype tools implementing our approach. These include a service enabling the component-aware runtime management of multi-component applications and a packager for generating the deployment artifacts needed to ship and manage applications on existing Docker-based container orchestrators.
- We showcase the effectiveness of our approach and prototype tools by reporting on how we exploited them to run a concrete case study based on an existing benchmark application.

It is worth highlighting that our solution is not intended to implement a new orchestrator from scratch, as for instance we did with the TosKer orchestration engine⁹. We instead aim at enabling a component-aware management of multi-component applications on top of existing, production-ready container orchestrator (e.g., Docker Swarm or Kubernetes), in order to exploit all features they already provide, e.g., multi-host deployment and network overlays. In this way we do not need to re-implement such features from scratch, and we can hence focus on seamlessly extending the orchestration support they provide.

The rest of this paper is organised as follows. Sects. 2 and 3 provides some background and a bird-eye view of the proposed approach, respectively. Sects. 4, 5 and 6 then introduce the open-source prototype tools implementing our approach. Sect. 7 shows how we exploited our approach to run a concrete case study based on an existing multi-component application. Finally, Sect. 8 and 9 discuss related work and draw some concluding remarks, respectively.

2 | BACKGROUND

2.1 | TOSCA

TOSCA¹⁴ (*Topology and Orchestration Specification for Cloud Applications*) is an OASIS standard whose main goals are to enable (i) the specification of portable cloud applications and (ii) the automation of their deployment and management. TOSCA provides a YAML-based and machine-readable modelling language that allows to describe cloud applications. Obtained specifications can then be processed to automate the deployment and management of the specified applications.

TOSCA allows to specify a cloud application as a service template, that is in turn composed by a topology template, and by the types needed to build such a topology template (Fig. 1). The topology template is a typed directed graph that describes the topological structure of a multi-component application. Its nodes (called node templates) model the application components, while its edges (called relationship templates) model the relations occurring among such components.

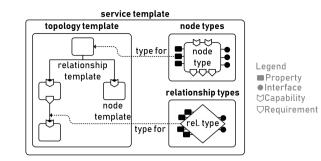


FIGURE 1 The TOSCA metamodel¹⁴.

Node templates and relationship templates are typed by means of node types and relationship types, respectively. A node type defines the observable properties of a component, its possible requirements, the capabilities it may offer to satisfy other components' requirements, and the interfaces through which it offers its management operations. Requirements and capabilities are also typed, to permit specifying the properties characterising them. A relationship type instead describes the observable properties of a relationship occurring between two application components. As the TOSCA type system supports inheritance, a node/relationship type can be defined by extending another, thus allowing the former to inherit the latter's properties, requirements, capabilities, interfaces, and operations (if any).

Node templates and relationship templates also specify the artifacts needed to actually realise their deployment or to implement their management operations. As TOSCA allows artifacts to represent contents of any type (e.g., scripts, executables, images, configuration files, etc.), the metadata needed to properly access and process them is described by means of artifact types.

Finally, to enable their actual deployment, TOSCA applications are packaged and distributed in CSARs (*Cloud Service ARchives*). A CSAR is a zip archive containing an application specification along with the concrete artifacts realising the deployment and management operations of its components.

2.2 | Modelling Multi-component, Docker-based Applications with TOSCA

In our previous work⁹, we defined a TOSCA-based representation for specifying the software components forming an application, as well as the Docker containers and Docker volumes used to form their runtime infrastructure. More precisely, three different TOSCA node types (Fig. 2) allow to distinguish among the Docker containers, Docker volumes and software components forming a multi-component application.

- tosker.nodes.Container allows to describe Docker containers, by indicating whether a container requires a connection
 (to another Docker container or to an application component), whether it has a generic dependency on another node
 in the topology, or whether it needs some persistent storage (hence requiring to be attached to a Docker volume). tos ker.nodes.Container also permits indicating whether a container can host an application component, whether it offers an
 endpoint where to connect to, or whether it offers a generic feature (to satisfy a generic dependency requirement of another
 container/application component). To complete the description, tosker.nodes.Container can contain properties (ports,
 env_variables, command, and share_data, respectively) for specifying the port mappings, the environment variables, the
 command to be executed when running the corresponding Docker container, the list of files and folders to share with the
 host. Finally, tosker.nodes.Container lists the operations to manage a container (which corresponds to the basic operations
 offered by the Docker platform to manage Docker containers⁷).
- tosker.nodes.Volume allows to specify Docker volumes, and it defines a capability attachment to indicate that a Docker volume can satisfy the storage requirements of Docker containers. It also lists the operations to manage a Docker volume (which corresponds to the operations to create and delete Docker volumes offered by the Docker platform⁷).
- tosker.nodes.Software allows to represent the software components forming a multi-component application. It allows to
 specify whether an application component requires a connection (to a Docker container or to another application component), whether it has a generic dependency on another node in the topology, and that it has to be hosted on a Docker
 container or on another component.tosker.nodes.Software also permits indicating whether an application component can

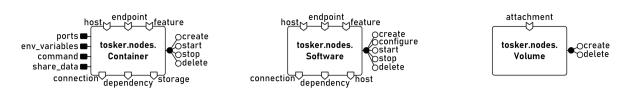


FIGURE 2 TOSCA node types for multi-component, Docker-based applications, viz., tosker.nodes.Container, tosker.nodes.Software, and tosker.nodes.Volume.

host another application component, whether it provides an *endpoint* where to connect to, or whether it offers a generic *feature* (to satisfy a generic *dependency* requirement of a container/application component). Finally, *tosker.nodes.Software* lists the operations to manage an application component by exploiting the TOSCA standard lifecycle interface¹⁴ (viz., *create*, *configure*, *start*, *stop*, *delete*).

The interconnections and interdependencies among the nodes forming a multi-component application can instead be specified by exploiting the TOSCA normative relationship types ¹⁴. The relationship type *tosca.relationships.AttachesTo* allows to attach a Docker volume to a Docker container. *tosca.relationships.ConnectsTo* allows to describe the network connections to establish between Docker containers and/or application components. *tosca.relationships.HostedOn* allows to indicate that an application component is hosted on another component or on a Docker container (e.g., to indicate that a web service is hosted on a web server, which is in turn hosted on a Docker container). Finally, *tosca.relationships.DependsOn* allows to represent generic dependencies between the nodes of a multi-component application (e.g., to denote that a component must be deployed before another, as the latter depends on the availability of the former to properly work).

Concrete examples of modelling of multi-component applications with the above recapped TOSCA representation can be found in Sect. 7.

3 | **BIRD-EYE VIEW OF OUR APPROACH**

4

Our ultimate objective is to enable a component-aware management of multi-component applications by piggybacking on existing container orchestrators (such as Docker Swarm and Kubernetes). We indeed aim at seamlessly extending the support they provide for orchestrating containers, so that the lifecycle of application components is not entangled to that of their hosting containers, but rather allowing components to be managed independently.

Fig. 3 provides an high-level overview on the orchestration approach we propose. The input is the TOSCA specification of a multi-component application. In the figure, the considered application is composed by three services (i.e., s1, s2 and s3) and three containers (i.e., c1, c2 and c3). Containers c1 and c2 are used as system containers ¹⁰, i.e., as lightweight virtual environments for hosting services s1 and s2 and service s3, respectively. The container c3 is instead a standalone container running its default main process. Services s1 and s3 also connect to s2 and c3 to deliver their businesses.

Given such a TOSCA application specification, a *Packager* generates the Docker Compose file allowing to deploy the application on top of Docker-compliant container orchestrators. The obtained artifact not only packages the components forming an application within the containers hosting them, but also seamlessly extends the application deployment by introducing some additional components enabling the desired component-aware orchestration.

- A *Unit* is included in each container packaging some application component (i.e., *c1* and *c2*). Each *Unit* is responsible of managing the lifecycle of the components packaged within the container it appears in, by launching the concrete artifacts (e.g., bash scripts) implementing their management operations.
- A *Manager* is included and packaged within a newly added container (i.e., *c4*). The *Manager* is responsible of interacting and coordinating the *Units*, in order to manage the components forming an application, and based on the commands issued by an application administrator.

With our approach, an application administrator can continue to deploy and manage the containers in an application by exploiting existing container orchestrators. She can then deploy and manage each software component forming her application by issuing commands to the containerised *Manager*, which will then properly forward it to the *Units* to enact the corresponding

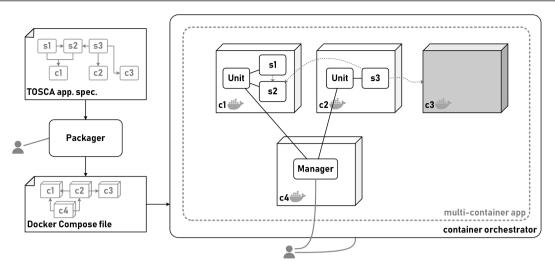


FIGURE 3 Bird-eye view of our approach for enabling a component-aware orchestration of the management multi-component applications on top of existing container orchestrators.

management operation. For instance, once the containers in Fig. 3 are all running, an application administrator may issue the commands to install and start service s1 to the *Manager*. The latter will forward the corresponding requests to the *Unit* in the container c1, which will launch the bash scripts implementing the to-be-enacted management operations.

It is worth noting that our approach seamlessly integrates with any Docker-compliant container orchestrator, as the newly introduced components (i.e., the *Manager* and the *Units*) are themselves packaged within Docker containers. In addition, by piggybacking on existing container orchestrator, our approach allows to uniformly manage containers, independently on whether they are used as lightweight virtual hosting environments for application components (as c1 e c2 in the figure) or whether they are used as standalone services (as c3 in the figure). This allows application administrators to choose whether to enable the fine-grain management of components or to couple their lifecycle to the containers they appear in. In the former case, she has to distinguish components and containers in the TOSCA application specification (and provide the artifacts implementing the lifecycle operations of such components), while in the latter case she just packages the components within the corresponding containers (by writing proper Dockerfiles — as she would be doing with current Docker-based orchestrators).

In the following, we illustrate how we concretely obtained the above illustrated orchestration solution, by designing and developing the TOSKOSE open-source toolset. We first show the issues and design choices for allowing *Units* to independently manage the software components packaged within a container (Sect. 4). We then show how we designed and developed the *Manager* to enable the orchestration of multi-component applications on top of existing orchestrators (Sect. 5), and how we implemented the *Packager* for generating a Docker-based artifacts from the TOSCA specification of an application (Sect. 6).

4 | MANAGING CONTAINERISED COMPONENTS

4.1 | Managing Multiple Components in a Container

The first challenge to tackle for enabling an approach like ours consists in allowing multiple components to coexist within a same Docker container, with each component also being independently manageable from the other components and from the container hosting them. Docker envisions the possibility of running multiple components in the same container¹⁵, by also recommending two possible solutions for doing so.

A naïve solution consists in wrapping all commands to install, configure and start the components to be hosted on a Docker container in a shell script. Bash job control can also be exploited to write down the shell script, e.g., to delay the starting of some components, or to execute processes implementing some of their management operations. The obtained shell script can then be executed as the main process of the container, hence meaning that the container continues to run until the shell script continues to run. This means that the shell script must not terminate until at least one of the components in the same container, their management operations in the same container, their management components in the same container.

lifecycle is still coupled to that of their hosting container. Another example supporting this statement comes from the restarting of a component that got stopped, which requires an application administrator to force a new execution of the shell script by tearing down its hosting container and starting a new container. The naïve approach indeed does not support remotely orchestrating the lifecycle of application components, in a way that is independent from the lifecycle of their hosting containers.

The other suggested solution is to exploit a process management system, like *Supervisor*. *Supervisor* (http://supervisord.org) allows users to control multiple processes on Unix-like operating systems, based on a client/server model. A server (called *supervisord*) is indeed responsible of starting sub-processes on demand, under client invocation or for handling some events (e.g., for restarting a child process that crashed or exited). *supervisord* manages each spawned sub-process for the entirety of its lifetime, by also taking care of signal management, logging and configuration (including auto-starting and restarting policies). Clients can then ask *supervisord* to spawn sub-processes through a command-line interface (called *supervisorctl*) or via a XML-RPC API (served by an HTTP server). Users can also customise *supervisord* by exploiting a configuration file, called *supervisord.conf*. The latter is loaded when Supevisor starts, and it is exploited to configure *supervisord, supervisorctl* and the HTTP-served XML-RPC API. This includes the definition of so-called program section, allowing to define and configure sub-processes that can be spawned on demand.

The *Supervisor*-based solution is hence more suited to our needs. Ad-hoc programs can be defined to allow independently executing the artifacts implementing the management operations of the components (with each program section devoted to a different lifecycle operation of a different component). Such operations can then be remotely orchestrated using the XML-RPC API natively offered by *Supervisor*. Following this initial idea, we hereafter show how we exploited *Supervisor* to implement the *Units* in our orchestration approach (Fig. 3). More precisely, we first discuss the issues characterising the management of multiple components within a same container and how *Supervisor* can help solving them (Sect. 4.2). We then illustrate how we implement *Units* as *Supervisor* instances (Sect. 4.3).

4.2 | Signal Management and Zombie Reaping

Managing multiple components in a same container inherently requires to be able to manage multiple processes in such container. A process indeed runs as the main process of the container (i.e., the process with PID 1), and each operation to manage a component requires to spawn a corresponding sub-process, e.g., executing the shell script implementing such operation. Two subsequent, potential issues must be taken into account while managing multiple processes within the same container, i.e., *signal management* and *zombie reaping*¹⁶.

4.2.1 | Signal Management

Signals sent to a Docker container are forwarded to its main process, which has hence to be configured so as to allow it to decide whether and how to forward them to its sub-processes. A striking example in this direction is the following: Suppose that a Docker container is stopped, by issuing the docker stop command. The latter sends a SIGTERM to the main process of the container for terminating its execution¹⁷. If the main process has not been configured to handle SIGTERM, it does not forward such signal to its child processes, which are hence not aware that the container is going to be dismissed. Afterwards, the Docker runtime dismisses the container by sending a SIGKILL signal, which results in killing uncleanly all processes running within the container. SIGKILL cannot be trapped, blocked or ignored and the processes are interrupted abnormally, possibly causing inconsistencies or data corruption¹⁸.

The main process of the container has hence to be configured to handle the signals it receives, by properly forwarding them to the processes running in the container. If adopting the naïve solution, this drastically complicates the writing of the shell script running as the main process of the Docker container, for which we would still have the issue of not being able to remotely orchestrate the lifecycle of the components running within the container. *Supervisor* instead natively supports signal management, hence making it more suitable to our needs.

4.2.2 | Zombie Reaping

Another challenge while trying to manage multiple processes within the same Docker container comes from the well-know PID 1 zombie reaping problem. In Unix-like systems, zombie processes are processes in a terminated state, waiting for their parent to exit completely and get their descriptor removed from the process table. The descriptor of a terminate process is kept in the process table until its parent reads its exit status and remove its descriptor from the table, hence "reaping the zombie" process¹⁸.

Unix-based systems are typically provided with full-fledged PID 1 processes (e.g., *systemd* in Debian), which support routines for reaping zombie processes. However, the PID 1 process of a Docker container is user-defined, and typically consists in the main process of the application running within the container. The latter typically does not feature any routine addressing the zombie reaping problem¹⁶.

Zombie processes are however harmful. Even if they are only consuming a little amount of memory to store their process descriptor, they keep their PID occupied. As Unix-like systems have a finite pool of PIDs, if zombies are accumulated at a very quick rate, the pool of available PIDs can be rapidly exhausted. This would result in preventing the spawning of other processes¹⁸. Given that we aim to managing multiple components within the same container, and since each call to lifecycle operation of a component results in new processes getting launched, zombie reaping has to be addressed¹⁶. However, neither the naïve solution nor that based on *Supervisor* are supporting zombie reaping¹⁵.

4.2.3 | Existing Approaches

Several solutions are addressing signal management and zombie reaping in Docker containers, with *dumb-init* (https://github.com/Yelp/dumb-init), *baseimage-docker* (https://github.com/phusion/baseimage-docker) and *tini* (https://github.com/krallin/tini) perhaps being the most prominent examples. They all share the baseline idea of wrapping the main process of a Docker container with a process acting as a proxy for signals and featuring a routing addressing zombie reaping. From developers' view-point, they provide a much lighter and usable solution with respect to including full-fledged init process systems (e.g., *sysvinit*, *upstart* or *systemd*) within Docker containers¹⁵.

The usage of *dumb-init* and *tini* is analogous. Both must be packaged within a Docker image and they must be used as main processes (wrapping the main process of the application) when a container is spawned from such image. *dumb-init* and *tini* will then take care of zombie reaping in a seamless way, by also forwarding signals to the process they wrap. Differently from *dumb-init*, *tini* is integrated with the Docker platform (since version 1.13). A boolean flag --init is supported by the commands dockerd and docker run, which allows to seamlessly feature signal forwarding and zombie reaping in a container spawned from an existing image, backed by *tini*.

Solutions like *dumb-init* and *tini* allow to resolve issues related to signal management and zombie reaping, but they however still lack of other essential features, e.g., remote control and logging. *baseimage-docker* is a step forward in this direction, as it offers an all-in-one Docker image based on Ubuntu, featuring an init process for signal management and zombie reaping.

4.3 | Our Solution

For addressing both signal management and zombie reaping, we exploited the *Supervisor*-based solution recommended by Docker¹⁵, in conjunction with *tini* (as the latter is already fully integrated with Docker). More precisely, we use *tini* as the main process of Docker containers, wrapping a *Supervisor* instance implementing the *Units* of our approach. In this way, *tini* cares about zombie reaping, and *Supervisor* cares about signal management, while at the same time enabling to remotely manage multiple processes within a same container. Such an approach brings other valuable advantages with respect to the main competitor among other existing approaches, i.e., *baseimage-docker*. Among such advantages, two are worth highlighting:

- *baseimage-docker* is coming only with a given distribution of Ubuntu, while *Supervisor* and *tini* work with any operating system distribution featured by a Docker container. This hence makes our approach applicable to a wider set of scenaria.
- baseimage-docker only support SSH to remotely access the internals of a container. *Supervisor* instead exposes a customisable XML-RPC API on top of a HTTP server. The API exposes methods for managing the lifecycle of both supervisord and its child processes, and it can be customised by exploiting an external INI-style configuration file. In particular, it is possible to define program sections, which result in offering remotely accessible methods that can be invoked on demand. The latter acts as an enabler for our orchestration approach, as the management operations associated with the components of an application can be implemented as *Supervisor* programs.

Units are implemented by packaging a (*tini*-wrapped) standalone instance of *Supervisor* in each container running one or more application components. It runs as the main process of the container, and it is configured to allow executing (on demand) the artifacts implementing the management operations of the components hosted by the container. The latter is obtained by providing the *Supervisor* instance with a configuration file containing a different program section for each management operation supported by the components hosted by the container, hence configuring the XML-RPC API of the *Supervisor* instance

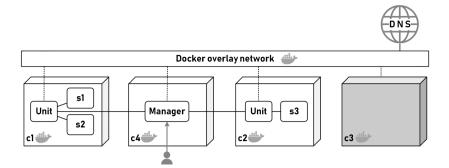


FIGURE 4 Interactions among *Manager* and *Units* for managing the lifecycle of containerised application components.

to feature a remotely accessible operation for each management operation of hosted components. The configuration file is automatically generated from the TOSCA specification of an application, and it is automatically packaged within each container of an application together with *Supervisor* (Sect. 6).

To enable the packaging of a standalone instance of *Supervisor*, we developed TOSKOSE UNIT (https://github.com/ di-unipi-socc/toskose-unit). TOSKOSE UNIT is a Docker image bundling a standalone instance of *Supervisor*, which is publicly available on the Docker Hub (https://hub.docker.com/r/diunipisocc/toskose-unit). Its purpose is to allow including a suitably configured instance of *Supervisor* in any Docker image of the containers forming the infrastructure of an application, which can be obtained by means of multi-stage Docker builds.

While developing TOSKOSE UNIT, we had to address an issue inherent to the usage of *Supervisor* within a Docker container. *Supervisor* is a Python application, hence requiring Python runtime to be available in the container running it. However, installing a Python interpreter in a Docker image can generate conflicts, if the Docker image is already featuring some Python interpreter. To address this issue, we exploited the PyInstaller "freezing" tool. PyInstaller "freezes" an existing Python program by creating a single-file executable that contains the application code and the Python interpreter to run it. In this way, we "freezed" *Supervisor* and created a bundle not needing any Python interpreter or module to be installed in the Docker containers running it, hence avoiding the risk for conflicts.

5 | ORCHESTRATING MULTI-COMPONENT APPLICATIONS

The second challenge to tackle consists in allowing to seamlessly manage the lifecycle of the components forming a TOSCA application, by enabling the remote invocation of their management operations, and by running them on top of existing Docker container orchestrators. Of course, the latter is because we wish to avoid reinventing the wheel, i.e., instead of re-designing a container orchestrator from scratch, we wish to piggyback on top of existing, production-ready orchestrators, also for allowing to reuse the capabilities they feature.

Existing container orchestrators already allow deploying and managing containers. For instance, given a specification of the containers to run and of their configuration, both Docker Swarm and Kubernetes can deploy such containers on a cluster of hosts by also configuring them as indicated. Docker Swarm and Kubernetes then proceed by orchestrating deployed containers, e.g., by applying them load balancing and scaling policies, for recovering failed instances, and to manage overlay networks or provisioning resources¹⁶.

At the same time, Docker containers are treated as "black-boxes" by existing container orchestrators, as the minimal entity that can be orchestrated is the container itself⁹. Our objective is to go a step forward, by enabling a component-aware orchestration of containerised applications, i.e., we aim at allowing to orchestrate the management of components running within the same container. To this end, we introduced *Units* (i.e., suitably configured Supervisor instances — Sect. 4) in each container running some component, so as to offer an XML-RPC API allowing to remotely invoke the operations for managing the lifecycle of the components it hosts. The next step is hence to find a suitable implementation of the *Manager* in our orchestration approach (Fig. 3), i.e., to introduce a containerised component in an application, which allows coordinating the management of each of its components by suitably interacting with the corresponding *Unit*.

Our baseline idea for doing so is illustrated in Fig. 4. Whenever the user wishes to execute a management operation on a component of her application, she invokes the *Manager* asking it to execute such operation. The *Manager* then forwards the

request to the *Unit* managing such component (i.e., it invokes the XML-RPC API of the Supervisor instance running within the container hosting the component). The interaction between the *Manager* and the *Unit* occurs through a Docker overlay network, and as soon as the *Unit* receives the request, it executes the required management operation (i.e., it runs the corresponding program section of the *Supervisor* configuration file). We hereafter illustrate a possible realisation of such an idea, given by the TOSKOSE MANAGER.

5.1 | The Architecture of the TOSKOSE MANAGER

The TOSKOSE MANAGER realises the *Manager* in our orchestration approach (Fig. 3), hence being responsible of coordinating *Units* to allow remotely managing the containerised components of an application, based on its TOSCA specification. The TOSKOSE MANAGER is intended to be included in an application as an additional containerised component, as this will allow managing it with Docker-based container orchestrators, together with all other containers forming an application.

Given that we are piggybacking on top of existing container orchestrators, we can exploit their capabilities for setting up the overlay network where the containers of an application will run (both for single-host and multi-host settings). This also means that, by properly setting network aliases, containers can intercommunicate by simply exploiting their hostnames on the overlay network, which will be automatically resolved by the network DNS. In addition, Docker-based container orchestrators allow running different applications in different virtual private networks. This has two main advantages for our purposes, namely (i) it permits securing the interactions among the components of an application, including the TOSKOSE MANAGER, and (ii) even if multiple instances of TOSKOSE MANAGER run on the same overlay network, they will not interfere one another.

With the above setting, TOSKOSE MANAGER only requires to know which container is hosting which components (to be able to interact with the *Unit* running in the same container) and the network aliases associated to the containers of an application. Such information is provided to TOSKOSE MANAGER by feeding it with the TOSCA application specification (from which it can retrieve the relations among components and containers) and an additional configuration file containing the network aliases associated to the container. The configuration file can be automatically generated, and both files are automatically injected to the TOSKOSE MANAGER by the TOSKOSE PACKAGER (Sect. 3).

To concretely implement the baseline idea shown in Fig. 4, the TOSKOSE MANAGER must hence feature (i) a remotely accessible API for allowing an application administrator to invoke the operation to manage the components of her application, (ii) a core processing module for identifying the *Units* where to forward requests, and (iii) a client for the XML-RPC API offered by the *Unit*, to concretely forward requests. It must also be capable of (iv) processing TOSCA application specifications. Fig. 5 shows the architecture of TOSKOSE MANAGER, designed to feature (i-iv), as well as to comply with the separation of concerns design principles to make it modular and extensible¹⁹.

RESTful API. A *RESTful API* allows the application administrator to invoke the execution of a management operation on a component of her application. The API is designed by following the Web API design paradigm²⁰, by partitioning it in three main logical layers, i.e., *Application, Business* and *Data*. The *Application* layer contains the controllers for translating HTTP incoming requests and outgoing responses, and for encoding and decoding their payloads, by also validating them. The *Business* layer is where the business logic of the API resides, with business rules and workflows defined to suitably interact with the *Data* layer and with the core of TOSKOSE MANAGER. The *Data* layer provides a storage of all information needed to orchestrate an application (i.e., component and container names, network aliases, etc.).

To enhance data encapsulation in inter-layer communications, *DTOs* and *Entities* are defined. These are used in the communication between the *Application* and *Business* layers, and between the *Business* and *Data* layers, respectively. Two other standalone modules are used for logging and error handling of the API, i.e., *Logging* and *Exceptions*, which are organised as cross-cutting concerns.

Management. The *Management* area contains the core module of TOSKOSE MANAGER, i.e., *App Manager*. The latter acts as a proxy between the *RESTful API* and the *Client* modules. It indeed receives requests from the API (e.g., executing a management operation on a component, or getting the status of all components), and it suitably interacts with the *Client* modules so that they interact and coordinate *Units* to carry out the requests.

The *Management* is also responsible of configuring the environment for allowing *App Manager* to run. It indeed contains the *App Config* and *Entrypoint* modules, which configure the runtime environment and run a web server used to host the *App Manager* (with the web server also being the main process run in the container of the TOSKOSE MANAGER). It also contains the the *Loader* and *Validator* modules, used for loading and validating the TOSCA application specification and the Toskose configuration file, which contain the information needed to orchestrate the specified application.

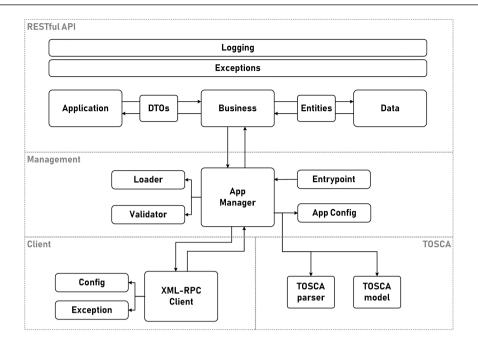


FIGURE 5 The architecture of the TOSKOSE MANAGER.

Client. The *Client* is responsible of communicating with the *Units* on the containers hosting the components of an application. It hence contains a *XML-RPC Client* allowing to invoke the XML-RPC API offered by the *Supervisor* instances implementing the *Units*. Whenever the *XML-RPC Client* is required by the *App Manager* to invoke an operation offered by a *Unit*, it builds and sends a HTTP request to the API of such *Unit*, which payload is structured according to the XML structure expected by the API of *Supervisor*. The *XML-RPC Client* is returned XML data representing the outcome of its request from the *Unit*, and it communicates the *App Manager* such an outcome.

For enforcing fine-grained failure management, and in accordance to separation of concerns design principles, error handling is kept separate from the rest of the application¹⁹. Errors are indeed handled by the *Exceptions* module, which is also part of the *Client* area.

TOSCA. The *TOSCA* area is responsible of the processing of TOSCA application specifications. It indeed features two modules, i.e., *TOSCA parser* and *TOSCA modelling*, intended to allow parsing TOSCA application specifications and to build an inmemory representation of specified applications.

5.2 | A Prototype Implementation of the TOSKOSE MANAGER

An open-source prototype implementation of the TOSKOSE MANAGER is publicly available on GitHub (https://github.com/ di-unipi-socc/toskose-manager), and it is also shipped as a Docker image publicly available on the Docker Hub (https://hub. docker.com/r/diunipisocc/toskose-manager). The prototype of TOSKOSE MANAGER is written in Python (v3.7.1), and we hereafter detail its implementation. More precisely, given that the *TOSCA* modules have been obtained by suitably extending the OpenStack TOSCA parser (https://github.com/openstack/tosca-parser), we shall focus on the implementation of the *RESTful API* and of the *Management* and *Client* areas.

RESTful API. Fig. 6 illustrates the architecture of the *RESTful API* featured by the prototype implementation of TOSKOSE MANAGER. The topmost component is a *Python WSGI HTTP Server*, where WSGI stands for "Web Server Gateway Interface" (which is a specification describing how a web server communicates with the web applications it hosts, and how they can be chained together to process a request). The HTTP Server is powered by Gunicorn (https://gunicorn.org), it implements the WSGI interface, and it permits running the web application implementing the API to be offered.

The *Application* layer of the API is then implemented by exploiting the Flask Python framework (https://palletsprojects. com/p/flask), extended with Flask-RESTPlus (https://flask-restplus.readthedocs.io). The latter has been included as it provides a collection of Python decorators and tools for quickly building RESTful APIs and exposing their documentation using the

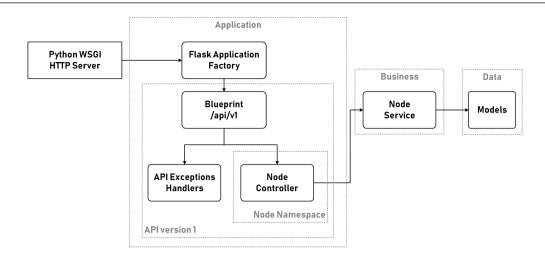


FIGURE 6 Architecture of the prototype implementation of the RESTful API of TOSKOSE MANAGER.

GET /node/ The list of nodes info
POST /node/reload Re-initialize the manager
GET /node/{node_id} The current state of a node
DELETE /node_id}/log Clear the log of a node
GET /node/{node_id}/log Fetch the log of a node
DELETE /node_id}/operations Stop all running lifecycle operations
GET /node/{node_id}/{component_id} Info about a hosted component
POST /node/{node_id}/{component_id}/{operation} Start a lifecycle operation
DELETE /node_id}/{component_id}/{operation} Stop a lifecycle operation
GET /node/{node_id}/{component_id}/{operation} Info about the status of a lifecycle operation
DELETE /node_id}/{component_id}/{operation}/log Clear the log of a lifecycle operation
GET /node/{node_id}/{component_id}/{operation}/log Fetch the log of a lifecycle operation

FIGURE 7 Snapshot of the HTTP methods offered by a running instance of the *RESTful API* of TOSKOSE MANAGER, obtained from the Swagger UI featured by Flask RESTPlus.

Swagger UI (https://swagger.io). In addition, Flask-RESTPluse enforces modularity of built APIs, hence making the current implementation of the *Application* layer of the *RESTful API* extensible for further developments.

The above setting has been obtained by suitably configuring the *Flask Application Factory*, which acts as the entrypoint of an application, by initialising the Flask environment where the application will run. This includes mounting extensions (such as Flask-RESTplus), as well as registering blueprints (i.e., logical groups partitioning the modules of an application based on the concerns they relate to, to enforce separation of concerns¹⁹). For instructing the *Flask Application Factory* to loading the current prototype of the API, we hence developed a *Blueprint /api/v1*. Notice that adding a different version of the API, or running different versions simultaneously, simply require to change or add another blueprint among those registered.

In addition, by exploiting the Flask RESTPlus extension, we logically organised the Blueprint using so-called "namespaces". A *Node Namespace* is indeed used, which is exploited to mark the *Node Controller* related to the resource /node. The latter is the root resource of *RESTful API*, and the *Node Controller* has been implemented so as to offer all methods shown in Fig. 7 The *Node Controller* is hence responsible of accepting incoming requests, which it decodes and validates by checking their

payload against an expected schema. Non-valid requests are refused, while valid requests are passed to the business layer for processing. Such a forwarding involves exchanging complex structured data, which is done by exploiting DTOs for enforcing data encapsulation.

The *Business* layer is implemented by the *Node Service*, which business rules allow to process incoming requests. Intuitively, it processes each request by retrieving information on involved application components, aggregating such data in the form of DTOs, and passing the request and retrieved data to the core of TOSKOSE MANAGER. In addition, the *Node Service* fetches and manipulates the logs of the *RESTful API*.

Management. The *App Manager* module in the *Management* area (Fig. 5) is the core module for managing multi-component application with TOSKOSE. Such a module maintains an in-memory representation of the managed application built from its TOSCA specification and enriched according to the Toskose configuration file, both loaded and validated during the initialization of the module. The TOSCA parsing is done by exploiting another Python module (i.e., *TOSCAParser*), which implementation is essentially wrapping the OpenStack TOSCA Parser library. Logging and error handling are also configured during the initialization of *App Manager*, by exploting the standalone *Loader* module.

After the initialization, the App Manager starts waiting for incoming requests for the (Node Service of the) RESTful API. Upon the receiving of a request, it instructs the XML-RPC Client to contact the Unit managing the component involved by the request.

Client. The *Client* area is implemented following the Factory method pattern, with the *App Manager* delegating to the *Client Factory* the decision to determine the concrete implementation of the client that must be used to interact with a *Unit*. Currently, the only available implementation is that for the XML-RPC API of *Supervisor*, which is obtained by exploiting the Python built-in xmlrpc.client. We anyway decided to implement clients using the Factory method pattern to allow TOSKOSE MANAGER to be extended to support multiple interaction protocols, in view of further developments.

6 | GENERATING DEPLOYABLE ARTIFACTS

The last brick needed for enabling our orchestration approach is the *Packager*, i.e., a solution that, given the TOSCA specification of an application, automatically generates the deployable artifacts needed to actually enact its deployment on top of existing, production-ready container orchestrators. The deployable artifacts must be such that *Units* (i.e., suitably configured Supervisor instances) are included within the containers hosting application components, and that a containerised TOSKOSE MANAGER is added to the application. The *Units* and the TOSKOSE MANAGER are indeed needed to enable a component-aware orchestration on top of the targeted container orchestrator. We hereafter present our solution for doing so, by first illustrating a solution for automating the generation of deployable artifacts, and by then presenting its prototype implementation, i.e., TOSKOSE PACKAGER.

6.1 | Automating the Generation of Deployable Artifacts

Fig. 8 illustrates a workflow that, given the TOSCA specification of an application, automatically generates the deployable artifacts for enabling a component-aware orchestration of multi-component applications on top of an existing container orchestrator. The workflow begins with the activities *TOSCA validation* and *Model generation*, which validate the TOSCA application specification and generate an in-memory representation of the specified application, respectively. If the given TOSCA specification is not valid, or if the *Model generation* fails, the workflow exits by returning error information.

The workflow then proceeds by dealing with the *Configuration management*, i.e., with the file indicating the configuration of the containers forming the application, including the network aliases and ports for reaching the components they host. If such a configuration file is missing or partial, the workflow automatically sets the missing fields to default values. The obtained configuration file is then used by the *Toskosing model* activity, which enriches the in-memory application representation with the information contained in the configuration file, as well as by adding the additional container packaging the TOSKOSE MANAGER.

The subsequent phase (*Contexts generation*) is repeated for each container of the application hosting some component (either being some original application component or the newly introduced TOSKOSE MANAGER). For each of such container, a Docker build context is prepared, by setting up a folder containing all files needed to build a Docker image. If a container is hosting application components, a so-called *Toskose Unit Context* is generated. The latter contains all the artifacts needed for deploying and managing the application components hosted on the container, i.e., the artifacts implementing an application component and those implementing its management operations. An automatically generated *Supervisor* configuration file is also included

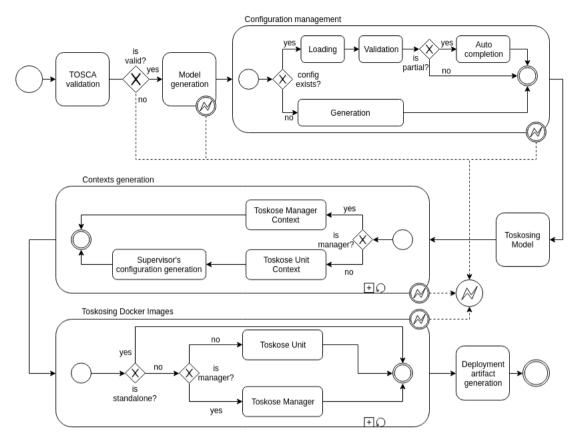


FIGURE 8 Workflow for automatically generating deployable artifacts, depicted according to the BPMN graphical notation²¹.

within the build context, which will then be used to configure the *Supervisor* instance implementing the *Unit* on the container (e.g., for ensuring that its XML-RPC API will offer methods for remotely invoking the management operations of the hosted components). If the processed container is instead that hosting the TOSKOSE MANAGER, the build context only contains the TOSCA specification and the Toskose configuration file of the application under processing.

The workflow then proceeds by *Toskosing Docker images*, i.e., preparing the Docker images of each containers of the application. If the container is a standalone container, the original image is kept. If instead the container is hosting some application component, two different activities are enacted, depending on whether the hosted components are original application components or the TOSKOSE MANAGER. In the former case, a new Docker image is built by combining the corresponding build context and the *Supervisor* bundle fetched from the TOSKOSE UNIT Docker image, by means of a multi-stage Dockerfile. In the latter case, the build context is instead combined with the Docker image packaging the TOSKOSE MANAGER, still by means of a multi-stage Dockerfile.

The deployable artifact generation process then completes with the *Deployment artifact generation* activity, which essentially takes the newly generated images of Docker containers (hereafter called *toskosed* images, for brevity) and combines them in a multi-container application deployment, e.g., a Docker Compose file. The *toskosed* images are configured in accordance with the in-memory application representation, so as to allow them to properly intercommunicate (both for running the application business and for allowing the TOSKOSE MANAGER to interact with the *Supevisor* instances implementing the *Units*).

6.2 | The Architecture of the TOSKOSE PACKAGER

Fig. 9 illustrates the architecture of TOSKOSE PACKAGER, our solution for generating the artifacts enabling the componentaware orchestration of an application on existing Docker-based container orchestrators, based on the workflow in Fig. 8. Still pursuing the aim of obtaining a modular and extensible solution, the architecture is designed in accordance with the separation of concerns design principles¹⁹. The architecture is indeed partitioned by devoting different sets of modules to different stages of the workflow.

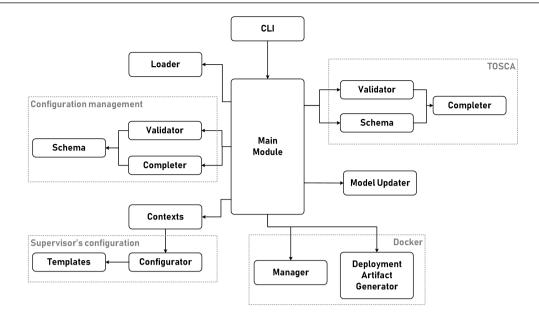


FIGURE 9 The architecture of the TOSKOSE PACKAGER.

A *CLI* module allows users to provide the TOSKOSE PACKAGER with the necessary input for starting the process for automating the generation of deployable artifacts, i.e., a TOSCA application specification and (optionally) a Toskose configuration file. The input is then passed to the *Main module*, which is in charge of coordinating the modules forming the architecture of TOSKOSE PACKAGER to suitably execute the activities of the workflow. It then first processes the input, by invoking the *Loader* module for actually importing the input files, and the modules in the *TOSCA* area for validating the TOSCA application specification and generating an in-memory representation the application.

The *Main Module* then interacts with the modules in the *Configuration management* area. The *Validator* module allows the *Main module* to validate the input Toskose configuration file, if any. The *Completer* module instead allows the *Main module* to complete the Toskose configuration file with default configurations, or to generate it from scratch if no configuration file is provided. Both the *Validator* and the *Completer* relies on a *Schema* module, indicating how the Toskose configuration file has to be structured, and which default values to employ for missing configurations. Once the configuration is ready, the *Model Updater* is used by the *Main Module* to enrich the in-memory application representation with the configuration information.

The *Main Module* continues by interacting with the *Contexts* module, which creates the build contexts for each container hosting some component, including that hosting the TOSKOSE MANAGER. For the containers hosting original application components, *Contexts* interacts with the *Configurator*, which allows to create the file for configuring the *Supervisor* instances implementing the *Units*, based on existing *Templates*.

Finally, the *Main Module* interacts with the modules in the *Docker* area. It first requires to the *Manager* to build the Docker images for the containers forming the application, which the *Manager* carries out by relying on the build features of the Docker Engine. The *Main Module* then requires the generation of the final *Deployment artifact* to the *Deployment Artifact Generator*.

6.3 | A Prototype Implementation of the TOSKOSE PACKAGER

An open-source prototype implementation of the TOSKOSE PACKAGER is publicly available on GitHub (https://github.com/ di-unipi-socc/toskose-packager). The prototype is written in Python (v3.6) and it has been released on the Python Package Index (https://pypi.org/project/toskose), to allow installing it with the command pip install toskose.

The prototype provides a command-line interface that takes as input a Cloud Service ARchive and (optionally) a Toskose configuration file, and it returns a Docker Compose artifact. The latter allows to deploy the application on Docker-based container orchestrators, with the latter being used to orchestrate the components of the application, while the orchestration of the components hosted on the containers being enabled by the RESTful API of TOSKOSE MANAGER (Sect. 5). Currently, the generated Docker Compose artifact is tested and fully working on Docker Swarm and on Kubernetes, with the latter requiring to first run Kompose (https://kompose.io) or Compose Object (https://github.com/docker/compose-on-kubernetes) to actually enact the deployment of the application.

We hereafter detail our prototype implementation of the TOSKOSE PACKAGER, by showing how each component of the architecture in Fig. 9 has been implemented.

CLI. The command-line interface (CLI) offers the following interface:

toskose [OPTIONS] CSAR_PATH [CONFIG_PATH]

where the optional argument OPTIONS is a list of options for customising the run of toskose. In particular, -o and --output-path PATH allow to specify the path where to place the output deployment artifacts, -p and --enable-push activate the automatic pushing of *toskosed* images on a Docker registry, --docker-url URL allows to define a custom entrypoint for the Docker Engine API, -q and --quiet reduce the output information messages, and --debug activates the debug mode.

The other arguments instead indicate the paths to the input files for the TOSKOSE PACKAGER. More precisely, CSAR_PATH indicates the path to a Cloud Service ARchive (CSAR), containing the TOSCA specification of an application and the artifacts realising the application and its management operations. The optional argument CONFIG_PATH instead provides the path to a Toskose configuration file.

Main Module. The *Main Module* is implemented as a Python module that is invoked by the command-line interface, which passes it the paths to the input files to be processed, and the processing options. It then starts coordinating the other modules of our prototype implementation of TOSKOSE PACKAGER to carry out the activities of the workflow in Fig. 8, in the given order.

The *Main Module* also generates to temporary directories using the Python tempfile library. A directory is used for storing the content of the (unpacked) CSAR archive, while the other one is used for storing the Docker build contexts. Both the directories are stored under /tmp and they are removed once the *Main Module* reaches the end of the workflow.

TOSCA. The implementation of the *Validator* provides the necessary for checking whether the input CSAR archive complies with the TOSCA standard¹⁴. It indeed allows to check whether the extension of the archive complies with admitted ones (i.e., .csar or .zip), as well as the directories composing the archive are organised as indicated by the TOSCA standard.

The *Parser* and *TOSCA Model* instead allow parsing the YAML file defining the TOSCA specification of an application and building an in-memory representation of the application. They are implemented by extending the OpenStack TOSCA parser (https://github.com/openstack/tosca-parser), in order to allow processing the TOSCA-based representation given by TosKer⁹.

Configuration. Toskose configuration files are specified in YAML, and they are structured in two YAML objects, i.e., nodes and manager. The object nodes is devoted to the configuration of the containers hosting application components, with one nested YAML object for each of such containers. Each nested object is given the same name as that of the container in the TOSCA application specification, and it allows to specify the alias associated to the container and the port where the XML-RPC API of the *Supervisor* instance implementing a *Unit* is offered. These are then used by the used by the TOSKOSE MANAGER for communicating with the *Unit* managing the components running in the container.

The object manager instead allows to provide the configuration information for the Docker container running the TOSKOSE MANAGER. It indeed allows specifying its alias on the Docker network, as well as the port, username and password for accessing the *RESTful API* of the TOSKOSE MANAGER

A Toskose configuration file can be optionally provided to our prototype implementation of the TOSKOSE PACKAGER. If provided, it is validated against the above illustrated schema by the implementation of the *Validator*. If something is missing, or if no configuration file is given, an auto-completion routine implementing the *Completer* allows to fill it with default values.

Model Updater. The implementation of the *Model Updater* adds the information contained in the Toskose configuration file to the in-memory representation of the processed application. More precisely, it first extends the application representation by setting environment variables to be defined in each container hosting a component, in such a way that the instance of *Supervisor* it runs is configured to listen on the indicated port. It also extends the representation of each container by setting properties needed for naming and tagging the correspondingly generated *toskosed* image (and optionally pushing it to a Docker registry).

The implementation of the *Model Updater* also includes an additional container to the in-memory application representation, devoted to hosting the TOSKOSE MANAGER. Such a container is then configured according to the specified configuration information, in a way similar to that described above. The choice of injecting the addition container during this activity simplifies the subsequent steps, which have to process only the in-memory application representation instead of fetching information from different sources.

Contexts generation. The *Contexts* module of our prototype implementation of the TOSKOSE PACKAGER fills a temporary folder devoted to Docker build contexts with a *Toskose Manager Context* for the container hosting the TOSKOSE MANAGER

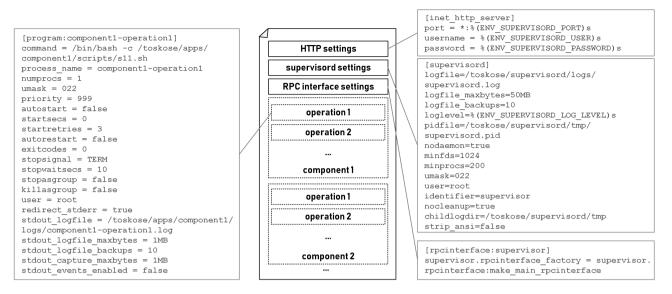


FIGURE 10 Template of the configuration of Supervisor injected in Docker containers to implement Units.

and a *Toskose Unit Context* for each container hosting some original application component. The *Toskose Manager Context* is devoted to storing the Toskose configuration file and the TOSCA specification of the application under processing, which are needed by the TOSKOSE MANAGER for enacting the management of the application.

Each *Toskose Unit Context* is assigned the name of the corresponding container. It is devoted to contain the artifacts realising the components hosted on the container, as well as the scripts implementing their management operations. The folder also contains a file supervisor.conf, providing all configuration information needed by the *Supervisor* instance running on the container for suitably implementing a *Unit*. The file supervisor.conf is generated by automatically extending a base template, which schema is in Fig. 10. The *HTTP settings* section configures the HTTP server used for offering the XML-RPC API of *Supervisor* by expanding the environment variables defining its configuration in the in-memory application representation. The *supervisor settings* section configures of *Supervisor*) with some default configurations, except for the logging level, which is fetched from the information stored in the in-memory application representation. The *RPC interface settings* section initialises the XML-RPC API of the *Supervisor* instance to run. The file is completed by including program sections allowing to remotely invoke the management operations of the application component hosted on the container.

Docker. The *toskosed* Docker images are built by the *Manager* module. The latter is implemented by exploiting the docker-py Python library (https://docker-py.readthedocs.io), which allows to interact with the API of the Docker Engine installed on a host, also for building Docker images. For each container to be *toskosed* (including the TOSKOSE MANAGER), the *Manager* implementation proceeds as follows. Firstly, it pulls the toskose-unit or toskose-manager Docker image from the Docker Hub and the Docker image associated with the container in the in-memory application from the specified registry, if they are not already available locally. It then instructs the Docker Engine to build the *toskosed* image, by passing it the application context, the pulled images and a multi-stage Dockerfile. If explicitly required by the user, the *Manager* module also proceeds with pushing *toskosed* images to a Docker registry.

The implementation of the *Deployment Artifact Generator* completes the workflow, by generating the Docker Compose file from the in-memory application representation. The containers of the application (including standalone containers) are added to the Docker compose file as services and configured as specified (e.g., by setting their network aliases and environment variables as indicated in the in-memory application representation). The automatically generated *toskosed* images are then used to implement the services corresponding to containers hosting some application component, while the Docker images originally indicated in the TOSCA application specification are used to implement those corresponding to standalone containers. In addition, Docker volumes are included in accordance to the in-memory application representation, and a Docker overlay network is set for allowing the deployment of the application in both single-host and multi-host infrastructure. The resulting Docker Compose file follows the schema shown in Fig. 11.

```
version: '3.7'
networks:
                                         # DOCKER NETWORK DEVOTED TO THE APPLICATION
 toskose-network:
    driver: "overlay"
                                         # setting the network to be an overlay network
    attachable: true
services:
  toskose-manager:
                                         # CONTAINER HOSTING THE TOSKOSE MANAGER
    image: <toskosed_image>
                                         # setting starting image to corresponding toskosed image
    networks:
                                         # attaching the container to the overlay network
      toskose-network:
        aliases:
                                         # setting the alias of the container on the overlay network
        - <alias>
    environment:
    - TOSKOSE_MANAGER_PORT=<port>
                                         # setting env. vars. needed by the Toskose Manager
    - TOSKOSE_APP_MODE=<mode>
    - SECRET_KEY=<secret_key>
    ports:
                                         # setting port mapping to expose the RESTful API to users
    - <api_port_mapping>
  <container_node_name>:
                                         # CONTAINER HOSTING SOME APPLICATION COMPONENT
    image: <toskosed_image>
                                         # setting starting image to corresponding toskosed image
    init: true
                                         # enabling Tini as init process
   networks:
                                         # attaching the container to the overlay network
      toskose-network:
        aliases:
        - <alias>
                                         # setting the alias of the container on the overlay network
    volumes:
    - <volume_mapping>
                                         # attaching container to specified volumes (if any)
    environment:
    - SUPERVISORD_ALIAS=<alias>
                                         # setting env. vars. for the Unit (i.e., Supervisor instance)
    - SUPERVISORD_PORT=<http_port>
    - SUPERVISORD_USER=<user>
    - SUPERVISORD_PASSWORD=<password>
    - SUPERVISORD_LOG_LEVEL=<log_level>
                                         # setting other env. vars. needed by the hosted components
   ports:
                                         # setting specified port mappings (if any)
    - ...
                                         # STANDALONE CONTAINER
  <standalone_container_node_name>
                                         # setting starting image to that indicated in the TOSCA spec
    image: <base_image>
   networks:
                                         # attaching the container to the overlay network
      toskose-network:
        aliases:
        - <alias>
                                         # setting the alias of the container on the overlay network
    volumes:
                                         # attaching container to specified volumes (if any)
    - <volume_mapping>
                                         # DOCKER VOLUMES (if any)
volumes:
```

FIGURE 11 Schema of the Docker Compose file generated by our prototype implementation of the TOSKOSE PACKAGER.

7 | CASE STUDY

We hereby illustrate a case study based on a multi-component application, which designed for testing application orchestrators in practice. We consider the *Thinking* application (https://github.com/di-unipi-socc/thinking), which we developed in the scope of our previous research²², and we show how TOSKOSE enables a component-aware orchestration of such application on Docker Swarm and Kubernetes, in a multi-host setting.

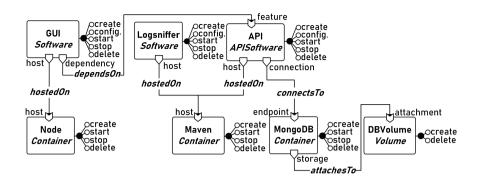


FIGURE 12 TOSCA-based representation of *Thinking*, obtained by exploiting the TOSCA types defined by TosKer⁹.

7.1 | The *Thinking* Application

Thinking is an open-source web application allowing its users to share thoughts on a web-based portal, so that other users can read them. *Thinking* is composed by three main components:

- A MongoDB database storing the collection of thoughts shared by users. The database is obtained by directly instantiating a MongoDB container, which needs to be attached to a volume where shared thoughts are persistently stored.
- A Java-based RESTful Web API to remotely access the database of shared thoughts. The API is hosted on a Maven container, and it requires to be connected to the MongoDB container (for remotely accessing the database of shared thoughts).
- A web-based GUI visualising all shared thoughts and allowing to insert new thoughts into the database. The GUI is hosted on a NodeJS container, and it depends on the availability of the API to properly work (as it sends HTTP requests to the API to retrieve/add shared thoughts).

For the purposes of this case study, and following the sidecar pattern, the application also includes a Logsniffer in the Maven container running the API of *Thinking*, which provides a web-based GUI for visualising and filtering the logs of the API.

The GUI, API and Logsniffer are also provided with a set of shell scripts implementing their lifecycle operations. The operation to install, configure, start, stop and uninstall each of such components are indeed implemented by the scripts install.sh, configure.sh, start.sh, stop.sh and uninstall.sh, respectively. The API is also equipped with the script push_default.sh, which can be optionally executed when the API is configured (but not running) to add a default set of thoughts to the MongoDB database.

7.2 | Modelling *Thinking* with TOSCA

By exploiting the TOSCA-based representation given by TosKer⁹ (and recapped in Sect. 2.2 for making this article selfcontained), the *Thinking* application can be modelled in TOSCA as shown in Fig. 12. *MongoDB* is modelled as a component of type *tosker.nodes.Container* and it is attached to the needed volume (*MongoDB*) through a relationship of type *tosca.relationships.AttachesTo. API* and *Logsniffer* are modelled as software components hosted on a component of type *tosker.nodes.Container* (i.e., *Maven*), with *API* being also connected to *MongoDB*. Notice that, while *Logsniffer* is of type *tosker.nodes.Software*, *API* is of type *tosker.nodes.APISoftware*, which extends *tosker.nodes.Software* to include the *push_default* operation featured by *API*. Finally, *GUI* is modelled as a component of type *tosker.nodes.Software*, which is hosted on a component of type *tosker.nodes.Container* (i.e., *Node*). The *GUI* is also indicated as depending on the availability of *API* to suitably serve its clients.

The corresponding TOSCA application specification is publicly available on GitHub, in the CSAR packaging such specification together with the artifacts implementing the components of *Thinking* and their management operations (https://github. com/di-unipi-socc/toskose-packager/blob/master/tests/data/thinking-v2/thinking-v2.csar). Concerning artifacts, it is worth noting that the artifact type used to implement *MongoDB* differ from those of *Maven* and *Node*, as *MongoDB* is qualified to be a standalone container, while *Maven* and *Node* are used as system containers for hosting application components. In addition, no artifact is provided for implementing the lifecycle operations of the containers and volume in *Thinking*, as our aim is to piggyback on existing container orchestrators, which natively feature such operations. nodes: maven: alias: maven port: 9456 user: user_21ty5 password: 1t5mYp4ss log_level: INFO docker: name: giulen/thinking-maven-toskosed tag: 0.1.3 node: alias: node port: 13450 user: user_a4bc2 password: p4ssw0rd log_level: DEBUG docker: name: giulen/thinking-node-toskosed tag: 2.1.5 manager: alias: toskose-manager port: 12000 user: admin_manager password: password_manager mode: production secret_key: my_secret docker: name: giulen/thinking-manager-toskosed tag: latest

```
nodes:
 maven:
    alias: maven
    port: 9001
    user: admin
    password: admin
    log_level: INFO
    docker:
      name: giulen/thinking-maven-toskosed
      tag: 0.1.3
      registry_password:
  node
    alias: node
    port: 9001
    user: admin
    password: admin
    log_level: INFO
    docker:
      name: giulen/thinking-node-toskosed
      tag: 2.1.5
      registry_password:
manager:
  alias: toskose-manager
  port: 10000
  user: admin
  password: admin
  mode: production
  secret_key: secret
  docker:
    name: giulen/thinking-manager-toskosed
    tag: latest
    registry_password:
```

(b)

(a)

FIGURE 13 Toskose configuration files used for generating a deployment of *Thinking*, with (a) being manually created and (b) being automatically generated by the TOSKOSE PACKAGER.

7.3 | Generating a Deployable Artifact for *Thinking*

We generated a Docker Compose file enabling a component-aware orchestration of the management of *Thinking* on Docker-based container orchestrators by running the TOSKOSE PACKAGER as follows:

```
$ toskose -p thinking.csar toskose.yml
```

where thinking.csar was a local copy of the CSAR packaging *Thinking* available on GitHub (see Sect. 7.2), and toskose.yml was the Toskose configuration file shown in Fig. 13(a). Fig. 13(b) instead shows the Toskose configuration file automatically generated by the TOSKOSE PACKAGER, which we obtained by not specifying any Toskose configuration file while running the TOSKOSE PACKAGER

\$ toskose -p thinking.csar

In both cases, -p was set to instruct the TOSKOSE PACKAGER to automatically push toskosed images to the Docker Hub.

Both runs of the TOSKOSE PACKAGER successfully generated a Docker Compose file for deploying *Thinking* on a Dockerbased container orchestrator. Fig. 14 shows the Docker Compose file obtained by running the TOSKOSE PACKAGER with the Toskose configuration file in Fig. 13(a). The file shows that the TOSKOSE MANAGER is automatically included among the containers to be deployed and how each container hosting some application component is implemented by a *toskosed* image, with the latter being suitably configured to run a *Supervisor* instance as a *Unit* managing the hosted components.

The Docker compose file in Fig. 14 is considered hereafter, as the docker-compose.yml file in the rest of our case study. For the sake of completeness, it is worth highlighting that all activities shown hereafter were successfully executed also with the Docker Compose file obtained by running the TOSKOSE PACKAGER with the Toskose configuration file in Fig. 13(b).

version: '3.7' services: maven: image: giulen/thinking-maven-toskosed:0.1.3 init: true networks. toskose-network: { aliases: [maven] } environment: - SUPERVISORD_ALIAS=maven - SUPERVISORD_PORT=9001 - SUPERVISORD_USER=user_21ty5 SUPERVISORD_PASSWORD=1t5mYp4ss SUPERVISORD_LOG_LEVEL=INFO _ INPUT_REPO=https://github.com/matteobogo/thoughts-api INPUT_BRANCH=master INPUT_DBURL=mongodb INPUT_DBPORT=27017 INPUT_DBNAME=thoughtsSharing _ INPUT_COLLECTIONNAME=thoughts INPUT_DATA=/toskose/apps/api/artifacts/default_data.csv - INPUT_PORT=8080 ports: ["8000:8080/tcp"] node: image: giulen/thinking-node-toskosed:2.1.5 init: true networks: toskose-network: { aliases: [node] } environment: - SUPERVISORD_ALIAS=node SUPERVISORD_PORT=9001 SUPERVISORD_USER=user_a4bc2 SUPERVISORD_PASSWORD=p4ssw0rd _ SUPERVISORD_LOG_LEVEL=DEBUG INPUT_REPO=https://github.com/matteobogo/thoughts-gui _ - INPUT_BRANCH=master INPUT_APIURL=localhost _ INPUT_APIPORT=8000 - INPUT_APIRESOURCE=thoughts ports: ["8080:3000/tcp"] mongodb: image: mongo:3.4 init: true networks: toskose-network: { volumes: ["dbvolume:/data/db"] } toskose-manager: image: giulen/thinking-manager-toskosed:latest init: true deploy: *id001 networks: toskose-network: { aliases: [toskose-manager] } environment: - TOSKOSE_MANAGER_PORT=12000 TOSKOSE_APP_MODE=production - SECRET_KEY=my_secret ports: ["12000:12000/tcp"] networks: toskose-network: { driver: "overlay", attachable: true } volumes: dbvolume:

FIGURE 14 Docker Compose file for deploying *Thinking*, automatically generated by the TOSKOSE PACKAGER.

7.4 | Deploying and Managing *Thinking* with Docker Swarm

To deploy the obtained Docker Compose file (i.e., docker-compose.yml) with Docker Swarm, we first exploited the Docker Machine tool (https://docs.docker.com/machine) to create Swarm cluster composed by four virtual machines (Fig. 15).

→ tmp docker-machine	ls								
NAME ACT	IVE DRIVE	R	STATE	URL		SWARM	DOCKER	ERRORS	
virtual-node-1 *	virtu	Jalbox	Running	tcp://192.168	8.99.114:2376		v18.09.9		
virtual-node-2 -	virtu	Jalbox	Running	tcp://192.168	8.99.115:2376		v18.09.9		
virtual-node-3 -	virtu	Jalbox	Running	tcp://192.168	8.99.116:2376		v18.09.9		
virtual-node-4 -	virtu	Jalbox	Running	tcp://192.168	8.99.117:2376		v18.09.9		
→ tmp docker node ls									
ID	H	IOSTNAME		STATUS	AVAILABILITY		MANAGER STA	TUS	ENGINE VERSION
70v67iic6qt0ox23uc43	tm41q * 🕔	/irtual-	node-1	Ready	Active		Leader		18.09.9
01doyi50ofqc1sewk7kl	zw84u v	/irtual-	node-2	Ready	Active				18.09.9
wv81zrzj3tpq0ua8m5pe	rut7g \	/irtual-	node-3	Ready	Active				18.09.9
lovqkjg8369ojm29k5eu	v5tn5 V	/irtual-	node-4	Ready	Active				18.09.9

FIGURE 15 Multi-host cluster provisioned for allowing the deployment of *Thinking* with Docker Swarm.

→ tmp docker stack deploycompose-file docker-compose.ymlorchestrator swarm thinking-stack									
Creating network thinking-stack toskose-network									
Creating service thinking-stack node									
Creating service thinking-stack mongodb									
Creating service th	inking-stack toskose-manager								
Creating service thinking-stack mayen									
→ tmp docker stack	ps thinking-stack								
ID	NAME IMAGE				NODE				
w9ocmq1zlx0s	thinking-stack maven.1	virtual-node-3							
m32m9zojmcug	thinking-stack toskose-manager.1 giulen/thinking-v2-manager-toskosed:latest virtual-node-2								
1nvy2a5vvia7	thinking-stack_mongodb.1 mongo:3.4 virtual-node-1								
p24rndong7n6	thinking-stack node.1	giulen/thi	virtual-node-4						
→ tmp docker service ls									
ID	NAME	MODE	REPLICAS	IMAGE					
j2sbjxn8em7m	thinking-stack maven	replicated	1/1	giulen/thinking-v2-maven-toskosed:0.1.3					
p6fzex24de05	thinking-stack_mongodb	replicated	1/1	mongo:3.4					
u3l5vzy8r2mf	thinking-stack_node	replicated	1/1	<pre>1/1 giulen/thinking-v2-node-toskosed:2.1.5</pre>					
xh5401y3az24	thinking-stack toskose-manager	replicated	ated 1/1 giulen/thinking-v2-manager-toskosed:latest						

FIGURE 16 Execution and outcomes of the command for deploying *Thinking* on our Swarm cluster.

Following the Docker documentation 23 , we then exploited the Docker Stack abstraction for actually enacting the deployment of *Thinking* on the Swarm cluster.

\$ docker stack deploy --compose-file docker-compose.yml --orchestrator swarm thinking-stack

Fig. 16 shows the execution and outcomes of the above command. Docker Swarm cared about spawning the containers in the *Thinking* application, and of distributing them on the Swarm cluster. Such containers were however only running their main processes, i.e., the TOSKOSE MANAGER in the case of thinking-stack_toskose-manager, the mongo application in the case of the standalone container thinking-stack_mongodb, and the *Supervisor* instances implementing the *Units* for the remaining two containers. The *GUI*, *API* and *Logsniffer* were instead not deployed yet, as the actual management of their lifecycle was to be orchestrated through the TOSKOSE MANAGER.

We hence completed the deployment of the *Thinking* application by exploiting the cURL command-line tool (https://curl. haxx.se) for interacting with the *RESTful API* offered by the TOSKOSE MANAGER. The latter was running on the virtual machine with IP address 192.168.99.115 (Figs. 15 and 16), and the API was configured to listen on port 12000 (Fig. 14). We hence installed the *API* by executing the following command:

```
$ curl -X POST -H "accept: application/json" \
    "http://192.168.99.115:12000/api/v1/node/maven/api/create"
```

Once installed, we configured the API and instructed it to populate the database with default thoughts by issuing:

```
$ curl -X POST -H "accept: application/json" \
    "http://192.168.99.115:12000/api/v1/node/maven/api/configure"
$ curl -X POST -H "accept: application/json" \
    "http://192.168.99.115:12000/api/v1/node/maven/api/push_default"
```

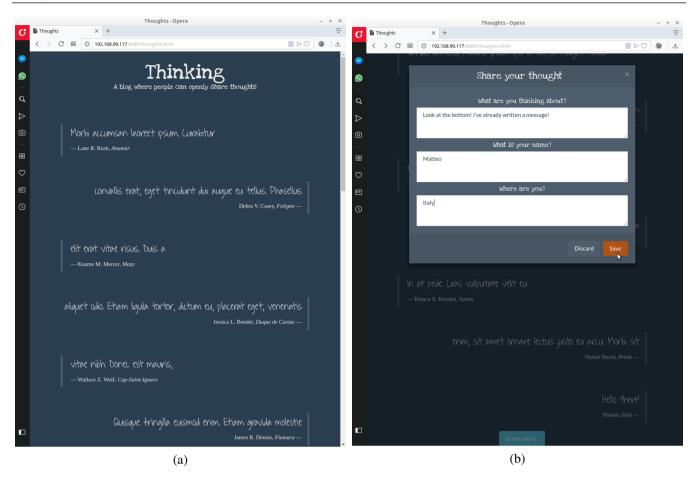


FIGURE 17 Snapshots of the running instance of *Thinking* obtained after completing its deployment. The snapshots show the web-based interfaces for (a) reading shared thoughts and for (b) sharing new thoughts.

We then started the API by executing

```
$ curl -X POST -H "accept: application/json" \
    "http://192.168.99.115:12000/api/v1/node/maven/api/start"
```

Similarly, we installed and started Logsniffer by executing

```
$ curl -X POST -H "accept: application/json" \
    "http://192.168.99.115:12000/api/v1/node/maven/logsniffer/create"
$ curl -X POST -H "accept: application/json" \
```

"http://192.168.99.115:12000/api/v1/node/maven/logsniffer/start"

and we installed, configured and started the GUI by executing

```
$ curl -X POST -H "accept: application/json" \
    "http://192.168.99.115:12000/api/v1/node/node/gui/create"
$ curl -X POST -H "accept: application/json" \
    "http://192.168.99.115:12000/api/v1/node/node/gui/configure"
$ curl -X POST -H "accept: application/json" \
    "http://192.168.99.115:12000/api/v1/node/node/gui/start"
```

As a result, we were able to reach the web-based portal of *Thinking* both for visualising shared thoughts and for sharing new thoughts (Fig. 17).

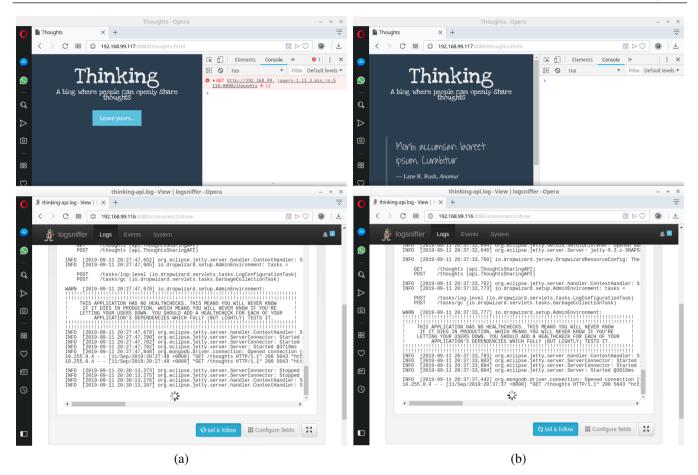


FIGURE 18 Snapshots of the running instance of *Thinking* and of the logs sniffed by the *Logsniffer*, (a) after stopping the *GUI* and (b) after restarting it.

It is worth highlighting how we came to complete the deployment of *Thinking*. We first fully relied on the capabilities of Docker Swarm to spawn and manage the Docker containers in *Thinking*, and the Docker volume needed by *MongoDB*. The TOSKOSE MANAGER then allowed us to manage the rest of the application at component-level, as we were able to remotely invoke the operations managing the lifecycle of the software components in *Thinking*.

To further experiment the component-aware orchestration enabled by our approach with the deployed instance of *Thinking*, we wished to stop and restart its *API*, by also observing the changes actually happening to the application. We hence stopped the *API* of *Thinking* by remotely invoking its *stop* management operation through the TOSKOSE MANAGER:

```
$ curl -X POST -H "accept: application/json" \
    "http://192.168.99.115:12000/api/v1/node/maven/api/stop"
```

As a result, if connecting to the web-portal shown by *Thinking*, none of the shared thoughts was displayed. Fig. 18(a) shows the reason for this, with the console of the browser notifying the failure of the GET request sent to the *API* for retrieving shared thoughts. Such an error is due to the fact that the *API* was successfully stopped, as indicated by the logs visualised by the *Logsniffer* (shown at the bottom of the same figure).

To proceed with our experiment, we restarted the *API*, i.e., we remotely invoked its management operation *start* through the RESTful API offered by TOSKOSE MANAGER.

\$ curl -X POST -H "accept: application/json" \
 "http://192.168.99.115:12000/api/v1/node/maven/api/start"

Fig. 18(b) shows the outcomes of such an invocation, i.e., the web-portal returned to visualise the shared thoughts, and the logs visualised by *Logsniffer* showed that the *API* was successfully restarted and returned serving HTTP requests.

→ tmp kompose up docker-compose.yml INFO We are going to create Kubernetes Deployments, Services and PersistentVolumeClaims for your Dockerized application. If you need different kind of resources, use the 'kompose convert' and 'kubectl create -f' commands instead.										
<pre>INF0 Deploying application in "default" namespace INF0 Successfully created Service: maven INF0 Successfully created Service: node INF0 Successfully created Service: toskose-manager INF0 Successfully created Pod: maven INF0 Successfully created Pod: mongodb INF0 Successfully created Pod: mongodb INF0 Successfully created PersistentVolumeClaim: dbvolume of size 100Mi. If your cluster has dynamic storage provisioning, you don't have to do anything. Otherwise you have to create PersistentVolume to make PVC work INF0 Successfully created Pod: node INF0 Successfully created Pod: toskose-manager</pre>										
Your application has been deployed to Kubernetes. You can run 'kubectl get deployment,svc,pods,pvc' for details. → tmp kubectl get deployment,svc,pods,pvc										
NAME service/kubernetes service/maven service/node service/toskose-manage	Clus	sterIP sterIP sterIP	CLUSTER-IP 10.96.0.1 10.104.191. 10.106.20.60 10.97.103.10	<none 58 <none 5 <none< td=""><td>></td><td>PORT(S) 443/TCP 8000/TCP,8082/TCF 8080/TCP 12000/TCP</td><td>AGE 15h 15s 15s 15s</td><td></td><td></td><td></td></none<></none </none 	>	PORT(S) 443/TCP 8000/TCP,8082/TCF 8080/TCP 12000/TCP	AGE 15h 15s 15s 15s			
pod/maven pod/mongodb pod/node	READY 1/1 1/1 1/1 1/1	STATUS Running Running Running Running		AGE 15s 15s 15s 15s						
NAME persis <u>t</u> entvolumeclaim/	/dbvolume	STATI Bound		187ba-5eb4	-463d-96		CAPACITY 100Mi	ACCESS MODES RWO	STORAGECLASS standard	AGE 15s

FIGURE 19 Execution and outcomes of the command for deploying *Thinking* on Kubernetes (with Kompose).

Even if simple, the above experiment further highlights how our approach enables a component-aware orchestration of the management of a multi-component application. We were indeed able to stop and restart a component (i.e., *API*), without requiring to stop the container running it or interfering with the other components running on the same container. *Logsniffer* continued to run during the whole experiment, allowing us to visualise the logs of the *API*. This also means that the container hosting *Logsniffer* and *API* continued to run, as expected (as its main process is the *Supervisor* instance implementing the *Unit* managing *API* and *Logsniffer*).

7.5 | Deploying and Managing *Thinking* with Kubernetes

We run two different experiments for deploying the Docker Compose file obtained from the TOSKOSE PACKAGER (i.e., docker-compose.yaml) on Kubernetes, differing on the tool exploited for doing so, i.e., Kompose (https://kompose.io/) and Compose Object (https://github.com/docker/compose-on-kubernetes). For the sake of conciseness, we hereafter only report on that based on Kompose.

After creating a Kubernetes cluster, we exploited Kompose to deploy the docker-compose.yaml file on the cluster. This was done by running

\$ kompose up docker-compose.yml

which outcomes are shown in Fig. 19. We then exploited the Kubernetes client (i.e., kubectl) to specify that the TOSKOSE MANAGER acts as Ingress node for our deployment⁸, hence allowing us to reach the RESTful API it offers.

\$ kubectl patch svc toskose-manager -p '{"spec":{"type":"LoadBalancer"}}'

We issued analogous commands to allow remotely accessing *GUI* and *API*, and this completed the deployment and configuration of the containers in *Thinking*, fully carried out by exploiting existing capabilities featured by the Kubernetes environment.

We then repeated the activities for deploying the software components in *Thinking*, and for stopping and restarting its *API*. In other words, we repeated the same sequence of curl commands shown in Sect. 7.4, with the only difference given by the IP address where the TOSKOSE MANAGER was listening (10.97.103.166 in this case, as shown in Fig. 19). All such commands successfully executed and resulted in the same outcomes as those presented in Sect. 7.4.

The above, together with the fact that the experiment run by exploiting Compose Object produced the same outcomes, show that we successfully ported the TOSKOSE-based orchestration approach on different Docker-based container orchestrators. It

also shows that, while the management of containers changed accordingly to the employed container orchestrator, the actual management of the components running on such containers remained unchanged, as it was independent from the employed container orchestrator.

8 | RELATED WORK

Various solutions exist for orchestrating the management of multi-component applications, based on TOSCA or Docker. The closest to ours is TosKer⁹, which —to the best of our knowledge— is currently the only solution enabling a component-aware orchestration of TOSCA-based application on top of Docker. It does so by implementing from scratch a new orchestration engine, allowing to coordinate the management of both the software components and the Docker containers forming an application. The TosKer engine is designed to run on a single host, which must be configured to provide root privileges to the engine itself (so as to allow it to spawn Docker containers and run application components on them). Our approach hence differs from that of TosKer, as we enable a component-aware management of TOSCA-based applications on top of existing container orchestrators, which natively support multi-host deployments. In addition, our approach does not need root privileges to properly work, hence making it suited also for scenarios where such privileges cannot be granted (e.g., on Container-as-a-Service platforms).

Another closely related approach is that tackled by the EDMM modelling and transformation framework^{24,25}. Even if not TOSCA-based, the EDMM modelling and transformation framework allows to specify the software components and Docker containers forming a multi-component application, and the operation allowing to manage each of components and containers²⁴. It then support the automated generation of the artifacts for deploying the application on top of existing orchestrators, including Docker Compose and Kubernetes²⁵. The latter essentially consists in creating deployment scripts coordinating the executable files implementing the management operations of the components of an application, in such a way that the dependencies occurring among such components are satisfied. It can hence be viewed as a solution for the component-aware deployment of multi-component applications on top of existing deployment platforms. However, once the deployment is enacted on a container orchestrator, the application is managed through such orchestrator, which considers containers as "black-boxes", i.e., not allowing to manage the components forming an application independently from the containers used to host them. Our approach hence differs from that EDMM-based, as we aim at supporting a component-aware management of multi-component applications during the term of multi-component applications are satisfied.

Considering containers as "black-boxes" is a baseline also shared by all other existing approaches trying to synergically combine the OASIS standard TOSCA and Docker for orchestrating multi-component applications. For instance, Kehrer and Blochinger²⁶ propose to use TOSCA for specifying the internals of a container, which are then manually built by developers to allow their orchestration (as "black-boxes") on top of Mesos. Our approach is instead intended to enable a component-aware management of multi-component applications on top of existing container orchestrators, by allowing to manage application components independently from their hosting containers.

Other approaches worth mentioning are OpenTOSCA²⁷, Alien4Cloud (http://alien4cloud.github.io), Cloudify (https:// cloudify.co), and the Apache ARIA TOSCA incubator (https://ariatosca.incubator.apache.org). OpenTOSCA is an open-source engine for deploying and managing TOSCA applications, which components include containers. Alien4Cloud, Cloudify and ARIA TOSCA also allow to manage multi-component applications, which components include Docker containers. However, they all differ from our approach to managing application since they Docker containers as "black-boxes", i.e., not supporting the management of software components separately from that of the containers hosting them.

SeaClouds²⁸ and Apache Brooklyn (https://brooklyn.apache.org) also relate to our approach. SeaClouds²⁸ is a middleware solution for deploying and managing multi-component applications on heterogeneous IaaS/PaaS cloud infrastructure. SeaClouds fully supports TOSCA, but it lacks a support for Docker containers. The latter makes SeaClouds not suitable to manage multi-component applications including Docker containers.

Apache Brooklyn (https://brooklyn.apache.org) instead natively supports both TOSCA and Docker containers. Thanks to its extension called *Brooklyn-TOSCA*²⁹, Brooklyn enables the management of the software components and Docker containers forming an application. However, Brooklyn treats Docker containers as black-boxes, and this does not permit managing the components of an application independently of that of the containers used to host them.

It is finally worth relating our approach with currently existing solutions for orchestrating multi-container Docker applications. Docker natively supports their orchestration by means of Docker Compose (https://docs.docker.com/compose), which allows to

indicate the images of the Docker containers forming an application, the virtual network to setup to allow the to intercommunicate, and the volumes to mount to persist their data. Based on such information, Docker Compose can enact the deployment of the specified application. Docker Compose however treats containers as "black-boxes", meaning that there is no information on which components are running within a container, and since it does not allow to orchestrate the management of application components independently from their hosting containers. In addition, no information is provided on the actual interdependencies and interconnections occurring among the components and containers of an application. Our approach instead allows to explicitly model the software components forming an application, to orchestrate their management independently from their hosting containers, and to explicitly consider the different types of relationships occurring among the components and containers in an application. This not only makes the interactions occurring among the components of an application easier to understand, but also brings various advantages in terms of reuse and maintenance¹³.

Other solutions worth mentioning are Docker swarm (https://docs.docker.com/engine/swarm), Kubernetes (https:// kubernetes.io), and Mesos (http://mesos.apache.org). Docker swarm permits creating a cluster of replicas of a Docker container, and seamlessly managing it on a cluster of hosts. Kubernetes and Mesos instead permit automating the deployment, scaling, and management of containerized applications over clusters of hosts. Docker swarm, Kubernetes and Mesos differ from our orchestration system as they focus on how to schedule and manage containers (as "black-boxes") on clusters of hosts, while we aim at piggybacking on top of them to enable a component-aware orchestration of the management of multi-component applications.

Similar considerations apply to ContainerCloudSim³⁰, which provides support for modelling and simulating containerized computing environments. ContainerCloudSim is based on CloudSim³¹, and it focuses on evaluating resource management techniques, such as container scheduling, placement and consolidation of containers in a data center, by abstracting from the application components actually running in such containers. Our solution instead focuses on allowing to independently manage the components forming an application while delegating container management to a container orchestrator.

9 | CONCLUSIONS

We presented a solution enabling the component-aware management of multi-component application on top of existing Dockerbased container orchestrators. More precisely, starting from an existing TOSCA-based representation for multi-component applications, we illustrated a novel approach allowing to manage the components forming an application independently from the Docker containers used to host them. We also introduced three open-source prototype tools implementing our approach. These are TOSKOSE UNIT (i.e., a bundling of *Supervisor* allowing to remotely manage the components running in a container), TOS-KOSE MANAGER (i.e., a containerised orchestrator allowing to coordinate the *Supervisor* instances running in the containers of the application), and TOSKOSE PACKAGER (i.e., a tool for automatically generating Docker-based deployable artifacts from the TOSCA specification of a multi-component application).

We also illustrated how our approach and prototype tools effectively enabled the component-aware management of an existing multi-component application (i.e., *Thinking*) on top of Docker Swarm and Kubernetes. After representing such applications in TOSCA, we exploited the TOSKOSE PACKAGER for generating deployable Docker Compose files. The latter were then effectively deployed with both Docker Swarm and Kubernetes on a cluster of virtual hosts. This allowed us to showcase that the containers forming the infrastructure of the considered applications were deployed and managed by relying on the capabilities of existing Docker-based container orchestrators, while the lifecycle of the software components hosted on such containers was independently orchestrated through the TOSKOSE MANAGER. The above held for both considered Docker container orchestrators (i.e., Docker Swarm and Kubernetes).

We believe that this paper can help researchers and practitioners wishing to independently orchestrate the components and containers forming an application. For instance, we discussed several issues while illustrating the development of our solution, e.g., signal management and zombie reaping, or potential conflicts when packaging multiple components in the same container. The discussion on issues and their possible solutions can be of help to researchers and practitioners needing to face similar problems while developing alternative solutions to ours, or simply because their applications need multiple components to reside in a single container.

In addition, the TOSKOSE open-source toolset can already be exploited (as-is) by researchers and practitioners to enable a component-aware orchestration of their applications on existing container orchestrators. The current prototype of TOSKOSE can also be exploited as the basis for the development of other research solutions or tools, or for validating existing approaches. For instance, we exploited TOSKOSE to further validate the outcomes of our former research, i.e., we exploited it to run TOSCA

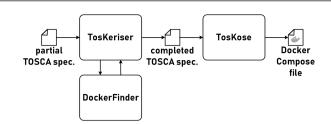


FIGURE 20 Open-source toolchain for generating deployable solutions from partial TOSCA application specifications, i.e., specifications only indicating the components forming an application and the requirements they need to run.

application specification automatically completed by TOSKERISER¹³. The latter is a tool for completing TOSCA application specifications, which automatically discovers and includes the Docker containers offering all what needed to run the components of an application, based on the information automatically retrieved by DOCKERFINDER³². Application specification generated by TOSKERISER were translated to Docker Compose files, which were then effectively orchestrated on existing Docker-based container orchestrators in a component-aware manner.

TOSKERISER, DOCKERFINDER and TOSKOSE actually form an open-source toolchain, which helps researchers and practitioners in automating the orchestration of multi-component applications with TOSCA and Docker (Fig. 20). They can indeed focus on only describing the components forming an application in TOSCA, and their runtime requirements. The TOSCA-based application representation is then automatically completed by TOSKERISER with the containers allowing to run its components, and then transformed by the TOSKOSE PACKAGER in a deployable solution (i.e., a Docker Compose file). The latter includes the TOSKOSE MANAGER and the *toskosed* images enabling a component-aware management of the application on top of existing Docker-based container orchestrators.

At the same time, the TOSKOSE open-source toolset requires to be further engineered to improve its capabilities. It currently features basic capabilities for scaling and self-healing components, fully relying on the mechanisms natively featured by the Docker-based container orchestrator employed for deploying an application. The minimal entity that can be scaled or self-healed is currently a container, and we are currently working on including support for component-aware scaling and self-healing.

We also plan to design and develop a support for automatically determining the workflow of management operations to invoke to allow an application to reach a desired configuration. Currently, the sequence of operations for reaching a given application configuration is to be manually issued by the application administrator. We plan to integrate existing analysis and planning techniques (e.g., based on Aeolus³³ or on management protocols²²), in such a way that the administrator just instructs the TOS-KOSE MANAGER with the desired application configuration, and the TOSKOSE MANAGER automatically issues the management operations allowing to reach and maintain such a configuration, even in presence of unexpected failures.

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