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Architecting with microservices: A systematic mapping study

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ABSTRACT

Context: A microservice architecture is composed of a set of small services, each running in its own process and communicating with lightweight mechanisms. Many aspects on architecting with microservices are still unexplored and existing research is still far from being crispy clear.

Objective: We aim at identifying, classifying, and evaluating the state of the art on architecting with microservices from the following perspectives: publication trends, focus of research, and potential for industrial adoption.

Method: We apply the systematic mapping methodology. We rigorously selected 103 primary studies and we defined and applied a classification framework to them for extracting key information for subsequent analysis. We synthesized the obtained data and produced a clear overview of the state of the art.

Results: This work contributes with (i) a *classification framework* for research studies on architecting with microservices, (ii) a *systematic map* of current research of the field, (iii) an evaluation of the potential for industrial adoption of research results, and (iv) a discussion of emerging *findings and implications* for future research.

Conclusion: This study provides a solid, rigorous, and replicable picture of the state of the art on architecting with microservices. Its results can benefit both researchers and practitioners of the field.

1. Introduction

Amazon, Netflix, LinkedIn, Spotify, SoundCloud and other companies (Fowler and Lewis, 2014; Villamizar et al., 2015; Yahia et al., 2016) have evolved their applications towards a microservice architecture (MSA). The most acknowledged definition of the microservices architectural style is the one provided by Fowler and Lewis (2014), which describes it as *an approach for developing a single application as a suite of small services, each running in its own process and communicating with lightweight mechanisms, often an HTTP resource API*.

Recently, the microservice architectural style has received significant attention from a research point of view. However, as of today it is difficult for both researchers and practitioners to have a clear view of existing research solutions for architecting with microservices. The **goal** of this paper is to characterize the current state of the art for understanding what we know about scientific research on architecting with microservices.

For achieving this goal we designed and conducted a systematic mapping study **methodology**. Specifically, we select 103 primary studies from 532 potentially relevant papers, we rigorously define a classification framework for categorizing research results on architecting with microservices, and we apply it to the 103 primary studies. Finally, we synthesize the obtained data to produce a clear overview of the state of the art in architecting with microservices. Also, we assess how research results on architecting with microservices can be potentially transferred and adopted in industrial projects. This assessment can play the role of reference framework for acting towards a smoother transfer of research results to practice.

The main **contributions** of this study include:

- a reusable framework for classifying, comparing, and evaluating architectural solutions, methods, and techniques (e.g., tactics, patterns, styles, views, models, reference architectures, or architectural languages) specific for microservices;
- an up-to-date map of the state of the art in architecting with microservices;
- an evaluation of the potential for industrial adoption of existing research results on architecting with microservices;
- an evidence-based discussion of the emerging research trends, patterns, and gaps, and their implications for future research on architecting with microservices.

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This study is an extended version of our previous research on architecting with microservices (Di Francesco et al., 2017b). The novelties added in this study are: (i) the extension of the set of primary studies from 71 to 103 entries because now we cover publications until the beginning of May 2017, (ii) a more in-depth elaboration of the extracted data, (iii) an orthogonal analysis about the potential interactions between various parameters of the classification framework, (iv) the analysis of the research trends over the years.

The **audience** of this study is composed of both (i) *researchers* interested to investigate on the microservices architectural style, and (ii) *practitioners* willing to understand and adopt existing research on architecting with microservices.

The remainder of this paper is organized as follows. In Section 2 we provide basic concepts about architecting with microservices. In Section 3 we present the design of the study. The elaborated results are reported in Sections 4, 5, and 6. Section 7 discusses the orthogonal findings of the study. Threats to validity and related work are described in Sections 8 and 9, respectively. Section 10 closes the paper.

2. Architecting with microservices

While there has not been a wide acceptance of a specific definition, a popular one was provided by Lewis and Fowler, which define the microservice architectural style as an approach to developing a single application as a suite of *small* services each running in its own process and communicating with *lightweight* mechanisms, often an HTTP resource API (Fowler and Lewis, 2014). Recurrent characteristics of the microservice architectural style are: (i) organization of the system around business capability, (ii) automated deployment, (iii) intelligence in the endpoints, and (iv) decentralized control of languages and data. This style allows to design architectures that should be flexible, modular and easy to evolve.

Microservice architectures can provide significant benefits. Among the important ones, there is the possibility to design, develop, test and release services with great agility. Infrastructure automation allows to reduce the manual effort involved in building, deploying and operating microservices, thus enabling continuous delivery. Decentralized governance and data management allow services to be independent, and avoid an application to standardize on a single technology. Microservice architectures are particularly suitable for cloud infrastructures, as they greatly benefit from cloud-enabled elasticity and rapid provisioning of resources.

Architecting with microservices, however, is not an easy task as it requires to manage a distributed architecture and its challenges, which include network latency and unreliability, fault tolerance, complex services' orchestration, data consistency and transaction management, and load balancing. Cloud infrastructures and new technologies play a fundamental role for realizing microservice architectures and managing the associated challenges and complexities.

An illustrative example of a microservice-based architecture is Netflix.[1] Netflix is implemented as an ecosystem of small, independently deployable, and independently scalable microservices. When requests come from client-side devices (e.g., smartphones, TVs, laptops), they reach the Netflix API orchestration service, which acts as an API gateway towards the rest of the ecosystem (i.e., it exposes a set of coarse-grained APIs and then routes incoming requests to the specific target microservices within the ecosystem). The Netflix API implements the logic to route, sequence, and parallelize incoming calls from the devices. Microservice-based systems must be designed to cope with failure (Fowler and Lewis, 2014), meaning that the application must be able to tolerate possible service failures either by recovering as fast as possible or by gracefully degrading its functionalities. At Netflix, this is achieved by having each microservice manage its own layer of persistence (as independently as possible from the other microservices), by pushing as much as possible towards stateless microservices, relying on real-time monitoring, using libraries for fast recovery of services, and by implementing the so-called circuit breaker architectural pattern for avoiding cascading failures (e.g., via the open-source Hystrix[2] library). Further details about the Netflix microservice-based architecture can be found in the Netflix technical blog[3].

3. Study design

In this research we follow the well-established guidelines for systematic mapping studies (Petersen et al., 2015; Kitchenham and Brereton, 2013). In this section we present the key aspects of the design of our study.

3.1. Goal and research questions

The goal of this study is to identify, classify, and evaluate the trends, focus, and potential for industrial adoption of existing research in architecting with microservices from a researcher's and practitioner's point of view. This abstract goal can be refined into the following research questions.

RQ1: What are the **publication trends** of research studies about architecting with microservices?
Rationale: academic research is a dynamic ecosystem, where a multitude of researchers and research groups investigate on specific scientific problems over time with different degrees of independence and different methodologies.
Relevance for researchers: the results of this research question help researchers in (i) quantifying the intensity of scientific interest on architecting with microservices, (ii) identifying the academic venues where related papers about architecting microservices are published, and (iii) identifying the academic venues where new results about architecting microservices may be better received (and appreciated) by the scientific community.
Relevance for practitioners: the results of this research question help practitioners in identifying the relevant venues where scientific knowledge is created, so to (i) take inspiration for solving problems which have been already targeted by researchers, (ii) get a more orthogonal and cross-organizational perspective with respect to architecting with microservices, and (iii) identify the research groups which are prominently contributing in the field, so to catch future collaboration opportunities.

RQ2: What is the **focus of research** on architecting with microservices?
Rationale: architecting microservices is a multi-faceted research topic, where researchers can focus on very different aspects (e.g., continuous integration, performance analysis, security, deployment elasticity, monitoring and fault tolerance), applying very different research methodologies (industrial case studies, empirical evaluations, feasibility studies, etc.), and providing different types of contributions (e.g., specific architectural tactics, architectural languages, etc.).
Relevance for researchers: by answering this research question we support researchers by providing (i) a solid foun-

[1] https://www.nginx.com/blog/microservices-at-netflix-architectural-best-practices/.

[2] https://github.com/Netflix/hystrix

[3] http://techblog.netflix.com.

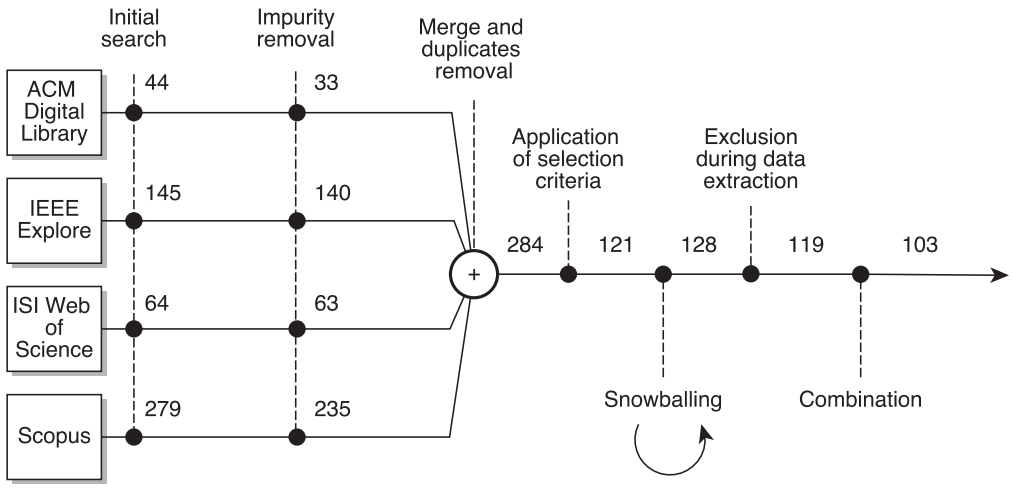


Fig. 1. Overview and numbers of the search and selection process.

dation for classifying existing (and future) research on architecting with microservices and (ii) an understanding of current research gaps in the state of the art on architecting with microservices.
Relevance for practitioners: the results of this research question help practitioners in (i) positioning themselves according to their organizational and technical needs (thanks to the classification framework) and (ii) effectively locate the research results which can be reused/customized for solving specific problems related to the microservices architectural style (e.g., how to efficiently and correctly perform integration testing of microservice-based systems).

RQ3: What is the **potential for industrial adoption** of existing research on architecting with microservices?
Rationale: while it is well known that microservices have their roots in industry, it is a fact that there are research groups focusing on them from an academic perspective. So it is natural to ask ourselves how the produced research findings and contributions can be actually transferred back to industry.
Relevance for researchers: by answering this research question we support researchers by assessing how and if the current state of the art on architecting with microservices is ready to be transferred and adopted in industry. Moreover, the results of this research question will trigger a discussion about the next steps for successfully transferring research products on microservice architectures to industry.
Relevance for practitioners: the results of this research question help practitioners in identifying those research products which are ready to be transferred to industry and which research groups are already collaborating with industry. Also, the results of our study support practitioners in identifying the solutions which are supported by (open-source) tools, and thus are one step closer to their application into an industrial context.

3.2. Search and selection process

In the following we present the stages of our search and selection process (see Fig. 1).

1. Initial search. In this stage we performed[4] automatic searches on electronic databases and indexing systems. The selection of these electronic databases and indexing systems was guided by: (i) the fact that they are the largest and most complete scientific databases and indexing systems in software engineering (Petersen et al., 2015; Kitchenham and Brereton, 2013), (ii) the fact that they have been recognised as being an effective means to conduct systematic literature studies in software engineering (Petersen et al., 2015), (iii) their high accessibility, and (iv) their ability to export search results to well-defined, computation-amenable formats. Our search string is shown in the listing below.

$$(architect* \ \mathbf{OR} \ design* \ \mathbf{OR} \ system \ \mathbf{OR} \ structur*) \ \mathbf{AND} \ (microservi* \ \mathbf{OR} \ micro\text{-}servi* \ \mathbf{OR} \ "micro \ servi"*)$$

Listing 1. Search string used for automatic research studies.

For consistency, the search string has been applied to title, abstract and keywords of papers in all electronic databases and indexing systems considered in this research.

2. Impurity removal. Due to the nature of the involved data sources, search results included also elements that were clearly not research papers, such as international standards, textbooks, book series, etc. In this stage we manually removed such impurius results from our set

3. Merging and duplicates removal. In this stage all relevant results from the first stage have been combined together into a single dataset.

4. Application of selection criteria. We considered all the selected studies and filtered them according to the following inclusion and exclusion criteria.

I1 - Studies focussing on architectural solutions, methods or techniques (e.g., tactics, patterns, styles, views, models, reference architectures, or architectural languages) specific for microservices.
I2 - Studies providing an evaluation of the architectural solution, method or technique (e.g., via formal analysis, controlled experiment, exploitation in industry, simple examples, etc.).
I3 - Studies subject to peer review.
I4 - Studies written in English.
E1 - Studies that, while focusing on microservices, do not explicitly deal with their architecture (e.g., studies focussing only on low-level technological aspects, the inner details of microservices, etc.).
E2 - Studies where microservices are only used as an example.
E3 - Secondary or tertiary studies (e.g., systematic literature reviews, surveys, etc.).

[4] The automatic searches were performed on May 8, 2017.

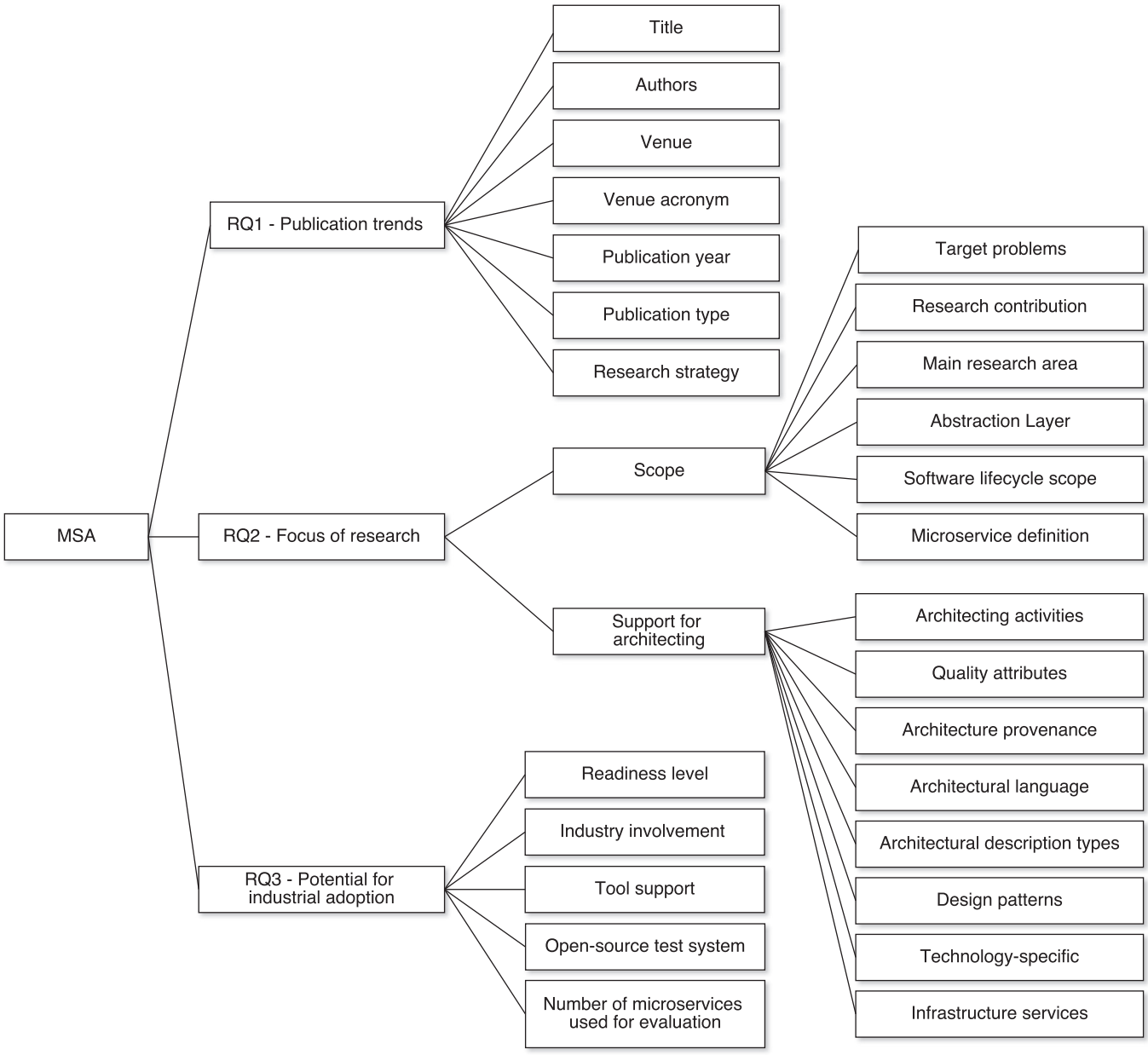


Fig. 2. Classification framework.

E4 - Studies in the form of tutorial papers, editorials, etc. because they do not provide enough information.
E5 - Studies not available as full-text.

Even if secondary studies have been excluded because of the E3 exclusion criterion, we considered them in our study for: (i) checking the completeness of our set of primary studies (i.e., if any relevant paper was missing from this study); (ii) identifying important issues to be analysed in this study; (iii) defining what is the contribution of this study to the literature (see Section 9).

5. Snowballing. In this phase we complemented the automatic search with a closed recursive backward and forward snowballing activity (Wohlin, 2014). In the backward snowballing we focussed on all the references of each considered study, whereas for the forward snowballing Google Scholar has been used to obtain those studies citing the current one (Wohlin, 2014).

6. Combination. If there were multiple papers on the same study, we kept a record of all of them and pointed them to a single study. For example, if a primary study was published in more than one paper (e.g., a conference paper extended to a journal version), only one instance has been considered as a primary study. Generally, the journal version has been preferred, since more complete, but both versions have been used in the data extraction and analysis of the publication trends (RQ1) phases. This step is necessary for ensuring completeness and traceability of the results (Wohlin et al., 2012).

3.3. Data extraction

In order to have a rigorous data extraction process and to ease the management of the extracted data, a well-structured classification framework has been rigorously designed. The resulting classification framework is shown in Fig. 2 and it is composed of three facets, each of them addressing its corresponding research question.

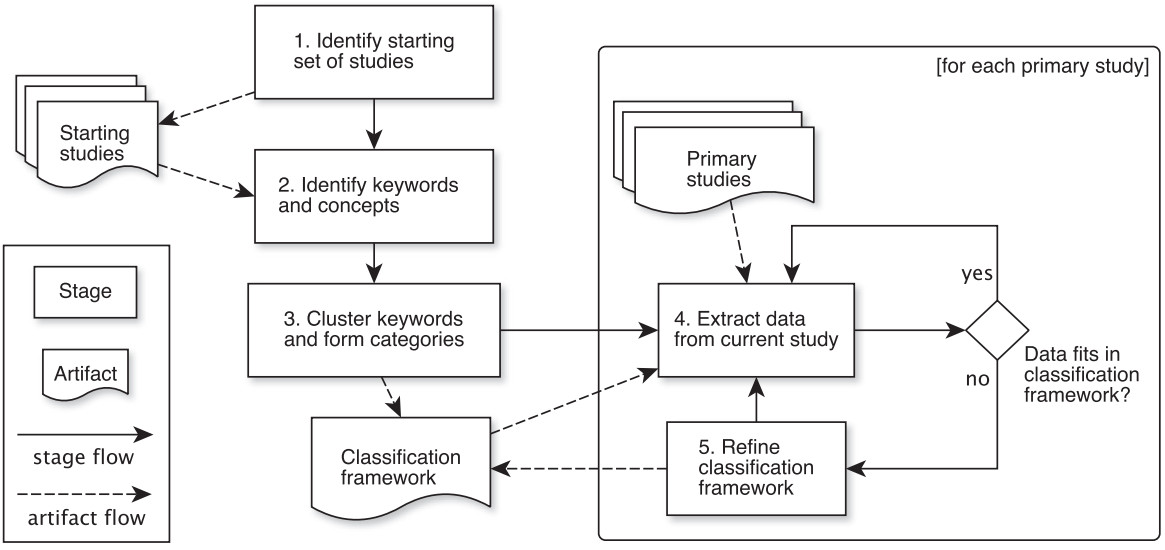


Fig. 3. Keywording process and data extraction for RQ2.

In the following we describe each facet of our classification framework.

Publications trends (RQ1). The parameters we considered to collect data about publication trends are: `publication year`, `publication venue` (e.g., conference, journal, etc.), and `research strategy` (e.g., solution proposal, opinion paper, etc.).

Focus of research (RQ2). We followed a systematic process called *keywording* for defining the categories of this facet of our classification framework. Goal of the keywording process is to effectively develop a classification framework so that it fits the primary studies and takes their research focus into account (Petersen et al., 2008). The following details each step of the process depicted in Fig. 3:

1. Identify starting set of studies. Two researchers (R1 and R2) randomly extracted 5 studies, which have been used as pilot studies.

2. Identify keywords and concepts. Three researchers (R1, R2, and R3) collected keywords and concepts by reading the full-text of each starting study.

3. Cluster keywords and form categories. Two researchers (R1 and R2) clustered the collected keywords and concepts into a set of emerging categories. The output of this stage is the initial version of the classification framework. Examples of emerging categories include: supported architecting activities, scope in the software lifecycle, considered design patterns, considered quality attributes (e.g., performance, reliability, security), etc. Next steps have been performed for each primary study.

4. Extract data from current study. A researcher (R1) extracted information about the current primary study to be analysed and (i) collected information according to the parameters of the classification framework and (ii) collected any kind of additional information that was considered relevant and that did not fit within any parameter of the classification framework. If the collected information about the current primary study fit completely within the classification framework, then we proceeded to analyze the next primary study, otherwise the classification framework was refined (this step involved three researchers, R1, R2, and R3)).

5. Refine comparison framework. Two researchers (R2 and R3) discussed together on the collected additional information. This discussion could result either in the correction of the performed classification or in the refinement of the classification framework in order to make it a better fit with the primary studies.

The above described process ended when no primary study to analyze was left. The specific parameters emerging from the keywording process are independent from each other and have been extracted independently; they are described in Section 5. Finally, in this phase we agreed that 9 analysed studies were semantically out of the scope of this research, so they have been excluded.

Potential for industrial adoption (RQ3). In order to analyse the potential for industrial adoption of microservices, we have classified and extracted five different parameters: (i) `readiness level` for assessing the maturity of the involved technologies, (ii) `industry involvement` for understanding how academic and industrial researchers collaborate on the topic, (iii) `tool support` for distinguishing between software-based or knowledge-based contributions, (iv) `open-source test system` for identifying existing benchmarks for microservice architectures, and (v) `number of microservices used for evaluation`.

3.4. Data synthesis

Our data synthesis activity can be divided into three main phases: vertical analysis, trend analysis, and horizontal analysis. When performing *vertical analysis*, we analyzed the extracted data to find trends and collect information about each parameter of our classification framework. When performing *trend analysis*, we focussed on how each possible value of all parameters of the classification framework evolves over time. When performing *horizontal analysis*, we used contingency tables for evaluating the actual existence of relations across different parameters of the classification framework, we made comparisons between pairs of parameters, and we identified perspectives of interest. In those phases we performed a combination of content analysis (for categorizing and coding the studies under broad thematic categories) and narrative synthesis (for explaining in details and interpreting the findings coming from the content analysis).

3.5. Replicability of the study

To allow easy replication and verification of our study, a complete replication package Di Francesco et al. (2017a) is publicly available to interested researchers. Our replication package includes: the detailed research protocol of this study, a document

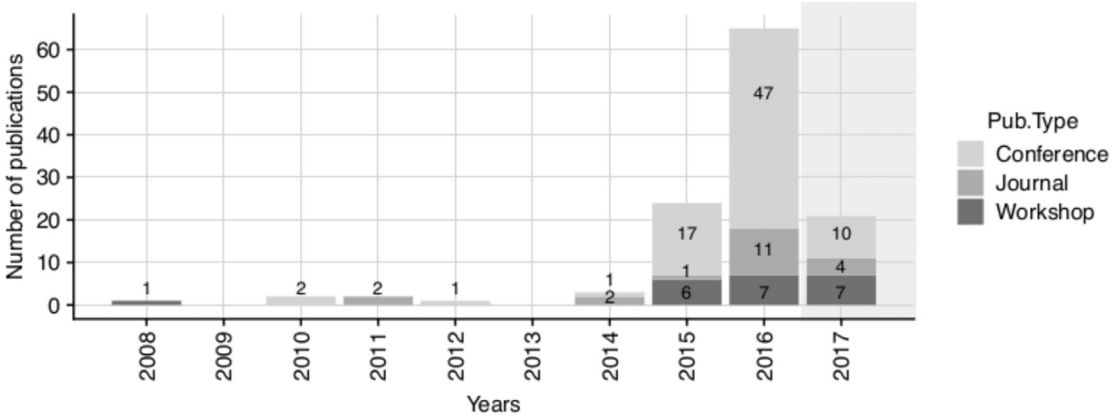


Fig. 4. Distribution of primary studies by year and by type of publication.

providing a precise definition of all the parameters of the classification framework, the list of all selected studies, raw data for each phase of the study, and the R scripts for checking, analyzing, and visualizing the extracted data.

4. Results - Publication trends (RQ1)

In this section we present the results we obtained when analyzing the publication trends on architecting with microservices. In order to provide a complete picture about the number and types of publications on the topic, in this section we consider all the selected publications, independently of the combination step we performed during the search and selection process (see Section 3.2). More specifically, for answering RQ1 we consider the total set of 119 primary studies, which includes both the entire set of 103 primary studies and the 16 primary studies resulting from the combination activity.

4.1. Obtained results (RQ1)

Publication years. Fig. 4 presents the distribution of publications on architecting with microservices over the years. The year 2017 is highlighted with a grey background to remark that data within this period is only partial, as the search and selection process was performed in May 2017.

The Figure emphasizes a clear confirmation of the scientific interest on architecting with microservices in the years 2015 through 2017. A very small number of publications have been produced until 2014, which is actually the first year in which (i) microservices started to attract the interest of large organizations, and (ii) the term microservice as architectural style was consistently used (Pahl and Jamshidi, 2016). As a confirmation, even if the six studies published before 2014 were about systems composed of small-scale lightweight services (P9, P60, P61, P62, P104, P105), they were referring to slightly different perspectives on microservices as they are considered today. For example, P9 considers microservices as low-level software components in the robotic domain, whereas P60 considers microservices as mobile services generated by end-users. Year 2015 signed a booming in the research field of architecting with microservices, with the trend increasing in 2016 and still growing in the first months of the year 2017.[5]

Publication types. Fig. 4 shows the publication types of the primary studies over the years. The high number of *conference* and *journal* papers indicate that architecting with microservices is progressing as research topic despite its relative young age; the relatively low number of *workshop* papers indicate that researchers commonly target more scientifically-rewarding publication types (like journals and conferences) when working on architecting with microservices.

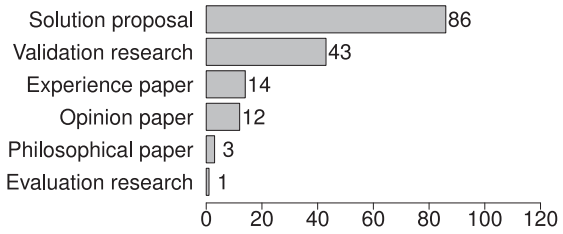


Fig. 5. Research strategies.

Publication venues. We can observe an extreme fragmentation in terms of publication venues, where research on architecting with microservices is spread across 91 venues spanning different research areas like cloud infrastructures, software engineering, software services, autonomic computing, software maintenance, etc. This result indicates that architecting with microservices is considered as an orthogonal research target with many cross-cutting concerns. In Table 1 the most targeted publication venues are reported. We can notice that researchers are mainly targeting specialized venues on architecting with microservices (i.e., AMS), cloud computing venues (i.e., IEEECC) and software architecture venues (i.e., ICSA). Researchers and practitioners can consider those venues as their starting points for their exploration into the state of the art on architecting with microservices.

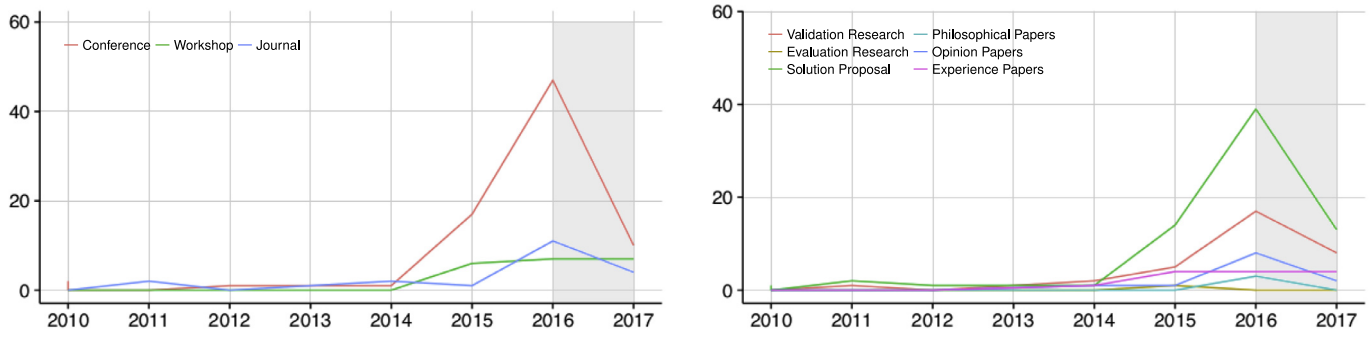
Research strategies. Since this parameter is general and independent from the research area, we reuse the comparison of research approaches proposed by Wieringa et al. (2006). We chose this comparison because (i) it has been widely used in various systematic mapping studies (e.g., Engström and Runeson, 2011; Mehmood and Jawawi, 2013; Petersen, 2011), and (ii) its categories are quite cost-effective to be identified by reading a paper without going into its very details (Petersen et al., 2008).

As shown in Fig. 5, here the clear winner is *solution proposal* (86/119). This result is due to the fact that the microservice architectural style is still in its infancy (we recall here that its first well acknowledged definition has been provided only in 2014) and not yet consolidated in any (not even de facto) standards. This results in a large number of researchers trying to propose their own solutions for either recurrent or specific problems (see Section 5.1 for the details on which problems are targeted). *Validation research* (43/119) is the second most recurrent research strategy, highlighting the fact that researchers are actually providing some level of evidence about their proposed solutions, e.g., by simulations, in-

[5] Our search process covers the research studies published until 8th May 2017.

Table 1
Publication venues.

Venue	#Studies
Workshop on Architecting with MicroServices (AMS)	5
IEEE Cloud Computing (IEEECC)	5
International Conference on Software Architecture (ICSA)	4
Service-Oriented System Engineering (SOSE)	3
Information Integration and Web-based Applications and Services (iiWAS)	3
Innovations in Clouds, Internet and Networks (ICIN)	3
International Conference on Performance Engineering (ICPE)	2
XSEDE Conference on Diversity, Big Data, and Science at Scale (XSEDE)	2
International Conference on Cloud Engineering (IC2E)	2
Enterprise Distributed Object Computing Workshop (EDOCW)	2
Cloud Computing Technology and Science (CloudCom)	2
EAI Summit on Smart Cities (EAI)	2
European Conference on Service-Oriented and Cloud Computing (ESOCC)	2
International Conference on Web Engineering (ICWE)	2
Utility and Cloud Computing (UCC)	2
Business Modeling and Software Design (BMSD)	2
CEUR	2
Other	74



(a) Publication types (b) Research strategies

Fig. 6. Trend analysis (RQ1).

the-lab experiments, prototypes, etc. At the other end of the spectrum, *evaluation research* is performed very rarely (1/119), meaning that industry- and practitioners-oriented studies (e.g., industrial case studies, action research, practitioner-targeted surveys) are not yet in the main focus of researchers today. Specifically, in P34 a case study conducted in a software company has been presented; in this context, the authors developed a Java application using both the monolithic approach and the microservice pattern. The fact that evaluation research is rarely performed has a negative impact on the potential for transferring current research results in industry. This suggests a gap that should be filled by future research on architecting with microservices, especially if we want to either (i) solve real problems coming from industrial scenarios, or (ii) push further the technology transfer of research results in industry.

4.2. Trend analysis (RQ1)

In this section we report our analysis of the research trends over the years for the parameters related to RQ1. We have analysed the research trends for *all* the parameters of the classification framework. However, some trends have been already discussed during the vertical analysis (e.g., the spike of conference publications in 2015 and 2016, see Fig. 6(a)) or do not have enough data points (e.g., the use of architectural languages – see Section 5.2), so in the following we focus exclusively on the most essential aspects we could observe. For the sake of completeness, we include in the replication package (Di Francesco et al., 2017a) of our study the figures showing the research trends for *all* parameters of the classification framework. In each figure, we have highlighted with a grey background the year 2017 to recall that the data within this period is partial, as the search and selection process was performed in May 2017.

For what concerns *research strategies*, we observe a growth of solution proposals from 2014. Studies proposing validation research are following the trend of solution proposals, but with a lower magnitude. Unfortunately, as previously discussed, evaluation research (i.e., the one involving industry- and practioners-oriented research methodologies) is still lagging behind and its

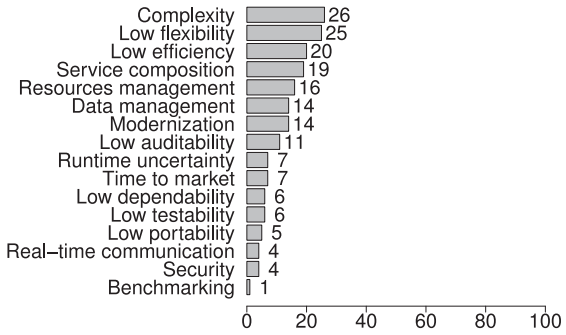


Fig. 7. Target problems.

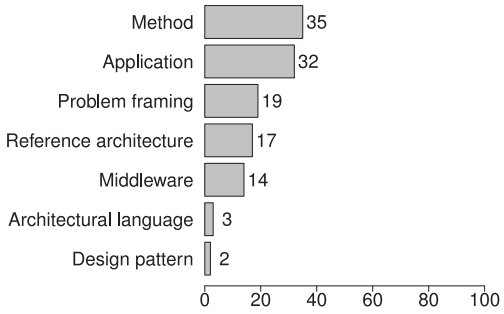


Fig. 8. Research contribution.

trend over the years seems not to be very promising. This confirms the urgency to fill the gap with respect to the industrial relevance of the performed evaluations.

Main findings:

- Year 2015 signed a booming monotonic increase in publication numbers with particular interest in conferences and journals (both increasing).
- The field is rooted in practice: publication venues are scattered across specific topics or application domains, and most publications propose specific solutions and validations thereof.
- Only one study applied industry- and practioners-oriented research methodologies (e.g., industrial case studies, action research), leaving a gap with respect to the industrial relevance of the performed evaluations.

5. Results - research focus (RQ2)

As described in Section 3.3, the part of classification framework related to RQ2 has been systematically defined. After this process we obtained two main categories related to the research focus on architecting with microservices, namely scope of the research (see Section 5.1) and support for architecting (see Section 5.2).

5.1. Scope of the research

With this category we provide information to help researchers and practitioners in putting into context research studies on architecting with microservices. In the following we discuss the obtained results.

Target problems. Fig. 7 presents the problems targeted by the primary studies. The obtained results confirm that if on the one hand microservices can help in achieving a good level of flexibility (e.g., by promoting low services coupling, higher maintainability), on the other hand adopting a microservice-based architecture may bring higher complexity. Interestingly, the bottom area of Fig. 7 shows problems that are related to system-level aspects like *time to market, low testability, low portability*, and *security*. Moreover, only one paper (P64) is addressing the problem of *benchmarking* microservice-based applications. These aspects have been extensively investigated in the software architecture area, but are still new to microservice architectures; this result is an indicator of a potentially relevant research gap needing attention in the future.

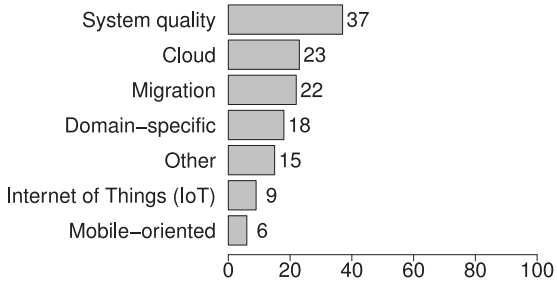


Fig. 9. Main research area.

Research contribution. By referring to Fig. 8, the realization of microservice-based *application* and the consistent number of *method* studies may indicate that the complexity in the realization of these systems is still very high. Interestingly, few papers are investigating *architectural languages* and *design patterns* for microservices, unveiling interesting gaps to be filled by the research community.

Main research area. The `main research area` is about the principal area of interest of the research to which the primary study belongs, e.g., cloud computing, system migration (see Fig. 9). The focus on the *system quality* (e.g., performance, maintainability) suggests that the microservice architectural style has direct impact on the design of a system and that researchers are still investigating how to leverage its characteristics.

A significant attention is also given to the use of microservices in *cloud* environments. Not surprisingly, a significant number of studies are investigating *migration* techniques in order to adopt and benefit of microservices starting from the so-called monolithic applications. An industrial survey on the activities and the challenges of migrating towards microservices (Di Francesco et al., 2018) provides insights to this topic from an industrial perspective.

If on the one side microservice architecture have been applied to recent technologies like *Internet of Things, mobile apps*, and other *domain-specific* fields as robotics (P9) and datacenters (P28), on the other side a significant number of studies are focusing on other research areas (not reported in the figure), such as microservice architecture recovery (P85), distinguishing characteristics between microservice- and service-oriented architectures (P77, P84), deployment cost models definition (P79).

Abstraction layer. As shown in Fig. 13, *microservices* can run on top of *(i)* a physical machine running an *operating system, (ii)* a machine running a *container* engine, *(iii)* a machine running a virtualized environment (in this setting the hypervisor is mapped as operating system), or *(iv)* a machine running a *container* engine on top of a virtualized environment.

As shown in Fig. 10, more than half of the studies focus on the *microservice* layer only, without considering any other layer. This result is also aligned with the recent advent of *serverless functions* running in the cloud, where the developer is asked to provide the business logic that should run in the cloud, whereas the operational overhead is taken care by the platform (e.g., AWS Lambda[6]).

[6] https://aws.amazon.com/lambda

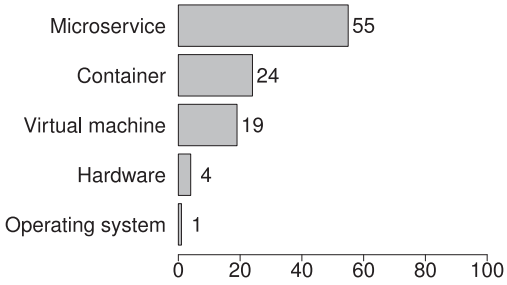


Fig. 10. Abstraction layer.

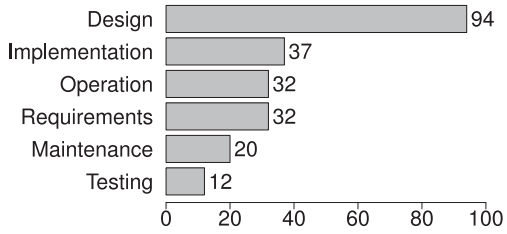


Fig. 11. Software lifecycle scope.

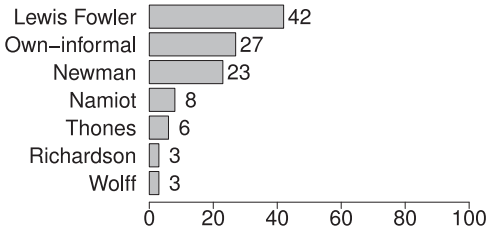


Fig. 12. Microservice architecture definition.

In this context, serverless platforms are able to transparently manage infrastructural and operations aspects of the system, such as its deployment and configuration, monitoring and logging (at different levels, like operating system, containers, communication, etc.), security facilities and patches, operating system, platforms, and libraries updates, management of the services lifecycle, services vertical and horizontal scaling, and so on.

Differently, other studies not only focus on microservices, but also consider the environment as an important aspect of the architecture. More specifically, the *container* and the *virtual machine* layers were discussed respectively in 24 and 19 studies. This particular focus on containerization and virtualization confirms them as key enabling technologies for MSA. Moreover, a few studies (P16, P27, P39, P75) also consider the possibility to run containers on top of virtual machines, thus combining the resource utilization benefits of virtual machines and the portability and efficiency of containerization (Jaramillo et al., 2016), which seems to be particularly suitable for offering microservices on the IaaS cloud model (Khazaei et al., 2016).

Software lifecycle scope. As shown in see Fig. 11, the number of studies on *design* is significantly higher than the number of those focusing on other lifecycle phases. In 32 primary studies the microservice architectural style is related with *operations* of deployment and configuration of the environment needed for the services in general. We have also investigated which studies relate the microservice architectural style with DevOps. Among the 103 primary studies, 30 of them discussed DevOps with two slightly different perspectives. On the one side, some consider DevOps as the set of practices intended to reduce the time between committing a change in the code base and rolling it out in production, while ensuring high quality (Bass et al., 2015). On the other side, DevOps deals with the goal of having the development and operations teams work closely together for achieving rapid and continuous release cycles (Fazio et al., 2016). A total of 32 studies explicitly discussed on the *requirements* of the microservice approach/application included in the study. This helps define the specific context information the microservice architectures are subject to. As an example, in P103 the authors discuss both functional and non-functional requirements when they use a microservice architecture to address key practical challenges in smart city platforms. Finally, given the trend in the scope of the studies, we conjecture that the areas of microservices *maintenance* and *testing* will attract further research when the fields of design, implementation and operation will gain more maturity.

Microservice architecture definition. In the primary studies, microservice architectures have been defined in several ways and in some cases even more than one single definition was reported. As shown in Fig. 12, the most recurring definition was the one provided by Fowler and Lewis (2014), followed by the ones given by Newman (2015), and others. In 27 of the 103 studies, the authors have either provided their own definition of microservices or have used an informal definition. Nevertheless, the definitions provided by Lewis & Fowler and Newman seem to start prevailing over other definitions.

5.2. Support for architecting

We characterize primary studies with respect to how they support architecture-specific concerns and activities, such as design patterns, support for specific quality attributes, recurrent infrastructural services.

Architecting activities. We have based our classification of `architecting activities` according to the introvert/extrovert nature of software architects discovered in Malavolta et al. (2013). The `introvert` nature regards the analysis and design of the software activities. It has been refined into the architecting activities defined by Li et al. (2013). The `extrovert` nature regards the communication between architects and other stakeholders. It has been further classified into the *providing information* and *getting input* parameters proposed by Kruchten (2008). Highlighted in darker gray in the figure, we can also observe how little investigation has been performed on `extrovert architecting activities`, i.e., *providing information* and *getting input* from other stakeholders of the system. From a research perspective, the low interest in these complementary activities indicates that there are areas of improvement in the engagement of customers and users, and also in the project management and communication with teams.

Quality attributes. Fig. 15 shows that *performance, maintainability*, and *functional suitability* are by far the most investigated quality attributes, while the remaining qualities are almost equally represented. Among the primary studies discussing *performance* (59/103), we have classified which of them have a special focus on scalability. It resulted that scalability aspects are addressed in 36 out of 59 studies, suggesting that many researchers seem to consider scalability as a sub-problem of performance when architecting with microservices.

Architecture provenance. According to our classification framework, an architecture is *designed* if it is created prior its implementation, otherwise it is considered as an *extracted* architecture. In Fig. 16, the overwhelming focus on *design* suggests that it is not easy to realize microservice architectures unless an actual analysis and design of the system is performed prior to its implementation.

Architectural language. An architectural language can be considered *as any form of expression used for architecture de-*

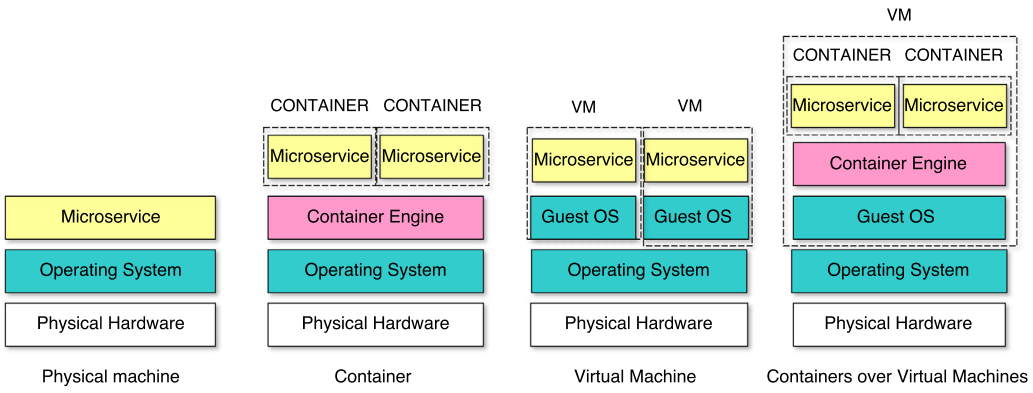


Fig. 13. Abstraction layers.

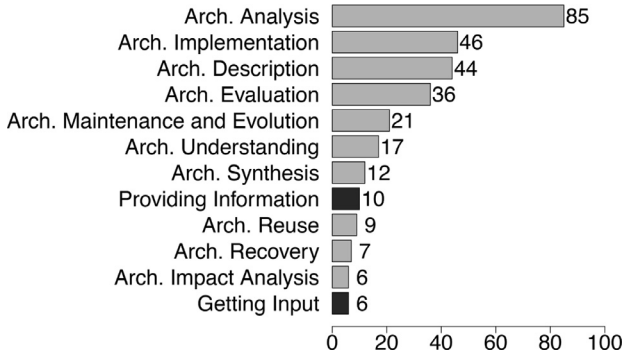


Fig. 14. Architecting activities.

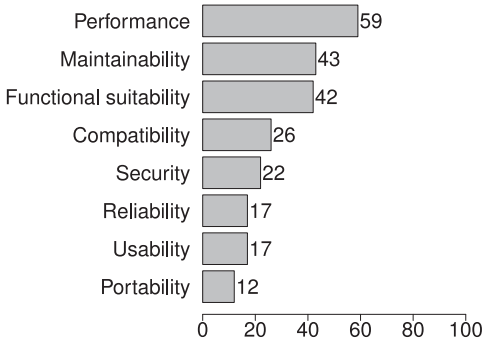


Fig. 15. Quality attributes.

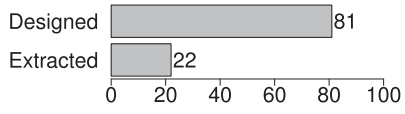


Fig. 16. Architecture provenance.

scription, ranging from box-and-line informal notations, UML models, to more formal Architecture Description Languages (ADLs) (Malavolta et al., 2013). From the analysis of the primary studies has emerged that the majority of the proposed architectures were described using *informal architectural languages*, while in few cases *UML* was used. Interestingly, nine different languages were either used or proposed as suitable languages for modeling specific aspects of microservice architectures: *BPMN* (P32, P49), *UML* (P41), *MicroART* (P85), *OCCIEx* (P57), *Medley* (P50), *KDM* (P72), *Diary* (P97), *Ciudad* (P60), and *Own-DSL* (P64). It is interesting to notice that the Oasis Topology and Orchestration Specification for Cloud Applications (TOSCA) (2013) standard has not been used by any of the primary studies for designing microservice architectures. TOSCA is a standard that can be used for representing portable cloud applications and supporting their life-cycle management (Bergmayr et al., 2018), and is a promising candidate for the microservice architectures (Ruiu et al., 2016; Lipton et al., 2018; Shalom, 2017).

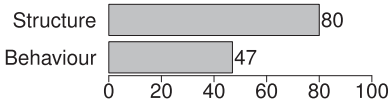


Fig. 17. Architecture description types.

From a researcher's point of view, the use of *informal architectural languages* and the lack of a predominant architectural language may lead to difficulties in the description and modeling of microservice architectures. We can conjecture that this concern can be addressed by working on a standard architecture language, which may help in having a shared common, industry-proven representation for microservice architectures. Proposing an architectural language for microservices helps architects in many activities; for example, it can help in reasoning about the system as a whole, performing analyses on the system qualities, coping with the dynamic and changing aspects of the application at runtime. Furthermore, an architectural language is a powerful communication instrument to enable better communication with both technical- (e.g., developers, architects) and non-technical stakeholders (e.g., customers and users) at the right level of abstraction and with a shared technical vocabulary.

Architecture description types. Fig. 17 shows that the architectures proposed were mostly described in terms of their *structural* aspects, while the *behavioral* aspects were addressed less often. The major focus of researchers on static rather than dynamic aspects gives another perspective about certain types of challenges inherently related to the definition of the microservices, as for example finding the proper level of granularity of each service or migrating legacy systems.

Technology-specific. We have classified as *technology-specific* the studies proposing solutions, methods or techniques that are specific to one or more particular technologies (e.g., Docker). A total of 75 primary studies were *not technology-specific*, while the remaining 28 studies were *technology-specific*. The predominance of *not technology-specific* studies is a good indicator because approaches and solutions can be reused across technologies. Differently, *technology-specific* studies bear the advantage of being more detailed, but their applicability and portability in the future might be limited. In the set of *technology-specific* studies, Docker is clearly

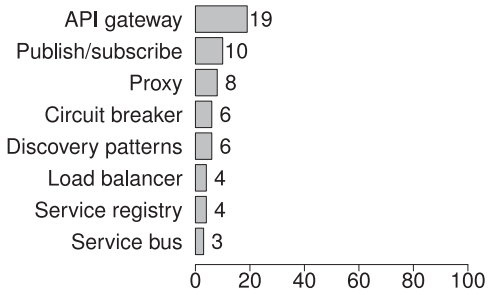


Fig. 18. Design patterns.

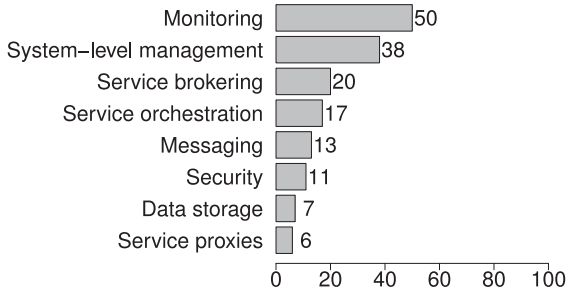


Fig. 19. Infrastructure services.

the most recurring technology (12/28) while other technologies are quite scattered, with a few occurrences of Java EE (P72, P78), Spring framework (P19, P63), Eureka (P19, P28), and other specific technologies (e.g., Serfnode (P31), KVM (P23)).

Design patterns. Each design pattern has been identified as reported in the primary studies, thus each pattern has to be considered disjoint from the others (e.g., if the *API Gateway* is used for implementing the *load balancing* pattern, we report each as a separate pattern). The set of discussed patterns is reported in Fig. 18. The most recurring design patterns when architecting with microservices are: *API gateway, Publish/subscribe, Proxy, Circuit breaker*, and *Discovery patterns*.

It is important to note that 7 primary studies (P10, P18, P29, P36, P42, P44, P48) have addressed or referred to a set of design patterns which have not been discussed in the other studies. In P10, four different patterns for implementing loose coupling in microservices are reported, namely: *location independence, communication independence, security independence*, and *instance independence* patterns. In P29, the authors report about the *ports and adaptor pattern*, also known as hexagonal architecture (Cockburn, 2007), and the *immutable server pattern* (Morris, 2014). In P36 a set of *data adapter* patterns for working with data provision mechanisms are addressed. In P42, the *bulkhead* pattern is presented to support fault isolation within a microservice. In P44, *cloud-focused* patterns such as the Twelve-Factor App (Wiggins, 2014), and *cloud computing* patterns are referred. In P48, authors not only address several existing patterns, but they propose a new pattern called *the database-is-the-service*.

Infrastructure services. These are the `infrastructure services` supporting non-functional tasks, as defined by Richards (2015). As shown in Fig. 19, microservice architectures, being inherently distributed, show a clear need for monitoring capabilities (e.g., logging, profiling) but also for *system level management* (e.g., health management, autoscaling) in order to leverage the underlying infrastructure efficiently. A significant research interest is pointing to *service brokering* and *service orchestration*, which confirms that service management capabilities are fundamental to this area.

5.3. Trend analysis (RQ2)

Fig. 20 summarizes our results for the trend analysis related to RQ2. In the following we will discuss only the most relevant trends.

When looking at the *main research areas* (see Fig. 20(c)), since 2015 we are seeing a growth of system-level quality, microservices in the cloud, and migration; we can conjecture that this trend will continue in the next years. Microservices in the context of mobile-enabled systems has a negative trend, meaning that in the last years researchers on architecting microservices seem to be less interested in microservices deployable on mobile devices in favour of microservices deployed in the back-end of mobile-based systems. This trend is in line with the classical definition of microservice, which is heavily influenced by concepts coming from containerization and cloud computing.

Research on microservices has a clear trend when considering the *software lifecycle scope* (see Fig. 20(e)), researchers are increasingly focussing on the design of microservice-based systems, followed by operations and implementation. Interestingly, requirements is recently starting to attract researchers' attention, hence suggesting that this trend might continue in the next years.

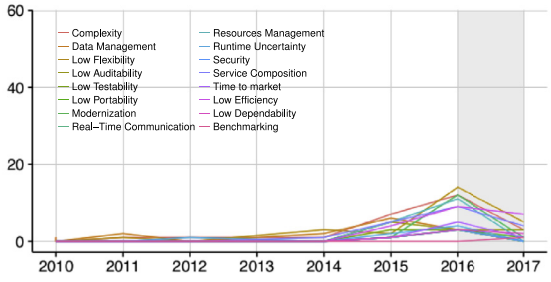
Looking at Fig. 20(g) (*architectural activities*), it is interesting to observe a spike in the focus on architectural analysis in 2015 and 2016, unveiling the fact that researchers are devising and applying (new) architecture analysis techniques in the last years. We believe that reasoning at the architectural level of abstraction allows those techniques to be applicable on large scale systems like the microservice-based ones.

It is clear that performance is the raising star in terms of *quality attribute* (see Fig. 20(h)), followed by a relatively strong interest over the years on maintainability and functional suitability. From the collected data, we can also observe that the scientific interest in security and usability is decreasing after 2015. We conjecture that the high degree of isolation provided by containers (e.g., by using Dockers namespaces) and resources limitations enforced in virtualized environments (e.g., limits for CPU load, I/O access, memory usage, and networking) may have played a role in this context.

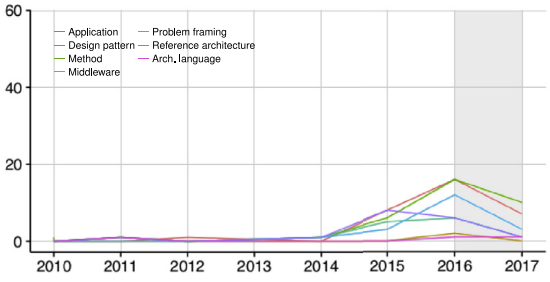
When looking at *infrastructure services* (Fig. 20(l)) we notice that monitoring (e.g., logging, profiling) and system level management (e.g., autoscaling, load balancing) have the most prominent growth in the last years. These are clearly the two types of infrastructure services that are attracting the strongest attention of researchers. We expect that this trend will continue in the future.

Main findings:

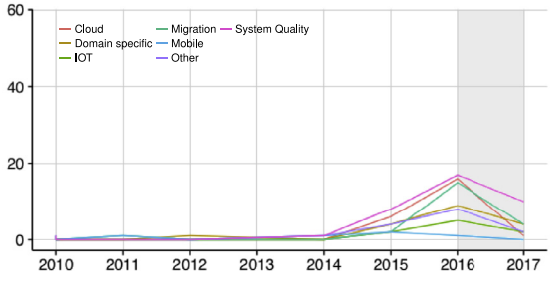
- Research *scope* involves problems that consolidate the need to master the tradeoffs between complexity and flexibility; here we can notice a strong focus on cloud and mobile paradigms, and legacy migration. Benchmarking is growing in 2017, potentially unveiling a promising future research direction. Requirements are starting to attract researchers' attention in recent years.
- Architecture analysis emerges as the most popular *architecting activity*. Results suggest software architecture as a powerful instrument for stakeholder engagement. Extrovert activities are raising since 2015, even if they are still not mainstream.
- The clear focus on infrastructure services has the potential to help devising new related patterns and styles and hence further leveraging cloud-based architecture models. In the set of investigated infrastructure services we observed that monitoring and system level manage-



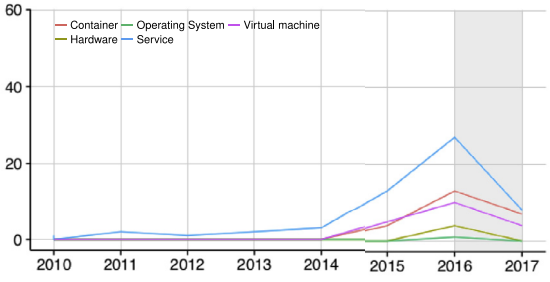
(a) Target problems



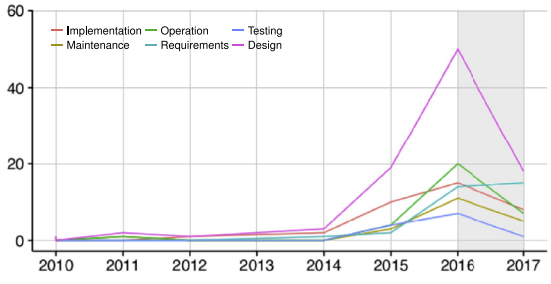
(b) Research contribution



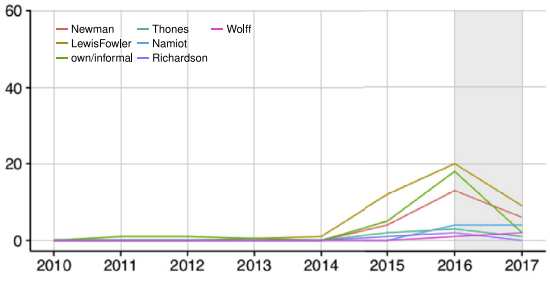
(c) Main research area



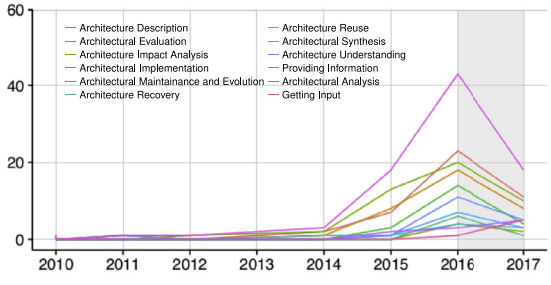
(d) Abstraction layer



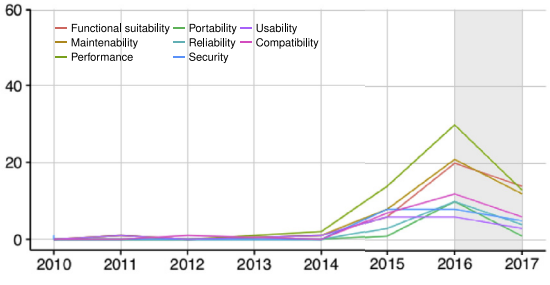
(e) Software lifecycle scope



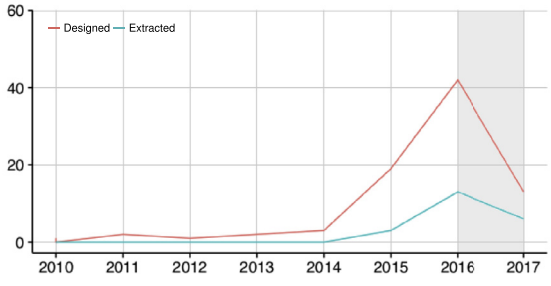
(f) Microservice definitions



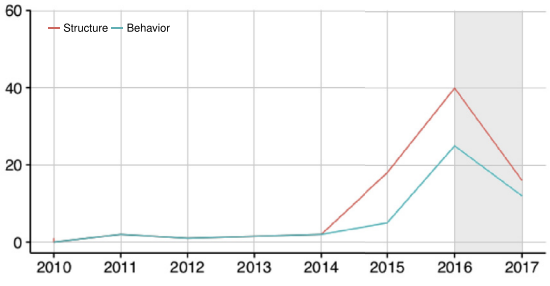
(g) Architecting activities



(h) Quality attributes

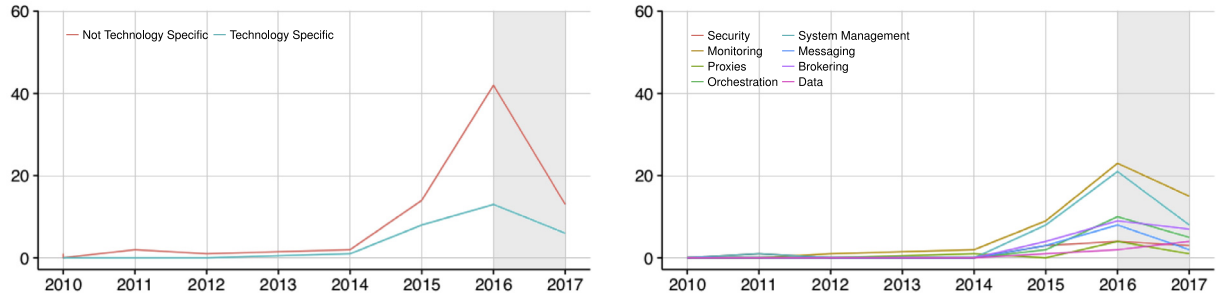


(i) Architecture provenance



(j) Architecture description types

Fig. 20. Trend analysis (RQ2).



(k) Technology specific (l) Infrastructure services

Fig. 20. Continued

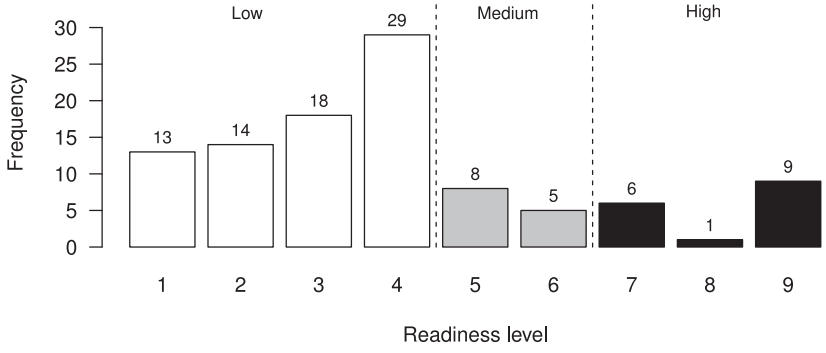


Fig. 21. Technology readiness levels.

ment (e.g., health management, autoscaling, load balancing) have the most prominent growth in the last years.

- An *industrial standard* describing the architecture of microservice-based systems does not yet exist. If present, it could help support the architecting activities of microservice-based systems better. The most promising standard in this direction is the OASIS standard for Topology and Orchestration Specification for Cloud Applications (TOSCA) that, with the proper customization, could be used in the future to model microservice architectures (Lipton et al., 2018).

6. Results - potential for industrial adoption (RQ3)

6.1. Obtained results (RQ3)

Readiness level. Defined by the systematic measurement system for assessing the maturity of a particular technology (Mankins, 1995), the technology readiness level (TRL) is an integer n where $1 \leq n \leq 9$. This measure has been used by the Horizon 2020 European Commission for the 2014/2015 work program.[7] We have classified the TRL of each primary study to emphasize the environment in which the proposed approach has been validated. Specifically, in the context of this study we classify the TRL of each primary study on a 3-level scale: (i) *low* TRL (i.e., TRL $\leq$ 4) means that a technology is either formulated, validated or demonstrated at most in **lab-based environments**, (ii) *medium* TRL (i.e., 5 $\leq$ TRL $\leq$ 6) means that a technology is either validated or demonstrated in industrially **relevant environment**, and (iii) *high* TRL (i.e., TRL $\geq$ 7) means that a technology is either completed, demonstrated, or proven in **operational environment**. Fig. 21 presents the TRL levels of our primary studies.

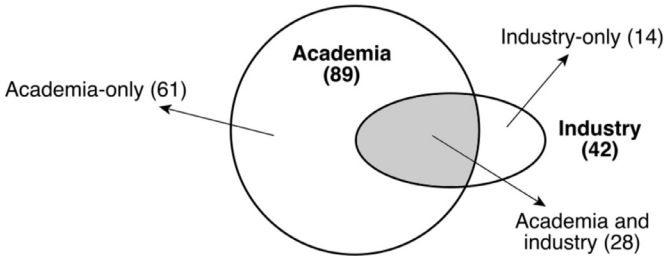


Fig. 22. Industry involvement.

The obtained results indicate that (i) research on architecting with microservices is still in its initial phase for what concerns the transferability of the developed technologies to industry and (ii) there is a relatively large number of studies (9/103) (P3, P7, P19, P33, P35, P59, P68, P83, P87) in which the actual system has been proven in its operational environment (TRL = 9).

Industry involvement. Here we classify each primary study as: *academic* if all authors are affiliated with universities or research centers, *industrial* if all authors are affiliated with some companies, or a *mix* of the previous two categories. As shown in Fig. 22, the results are encouraging, as in almost half of the primary studies (42/103), there is the involvement of at least one industrial researcher or practitioner; this suggests some knowledge exchange between academia and industry.

Tool support. In the context of this study a tool can be considered as an *instance that may represent a precise version of an automated tool or a written procedure* (Jaccheri et al., 1998). Based on the given definition, we categorize a tool either as *software-based* or *knowledge-based*. Overall, 54 primary studies provided software-based tools and 77 primary studies provided knowledg-based tools.

[7] http://ec.europa.eu/research/participants/data/ref/h2020/wp/2014_2015/annexes/h2020-wp1415-annex-g-trl_en.pdf.

From a research point of view, this result indicates the need to support knowledge-based tools with more software-based tools in order to demonstrate how effective knowledge-based tools are and how they can be compared one another. This can help researchers and practitioners to improve the overall quality of microservice-based systems.

It is important to notice that this parameter can be related to the *Research contribution* parameter of our classification framework (see Section 5.1). Indeed, here we are focussing on whether the proposed approach is *proposing* a specific tool, procedure, or guideline (or a combination thereof), as opposed to the *main research contribution*, which may be about the description of a problem, a new application of the microservices architectural style, etc.

Open-source test system. When screening the 103 primary studies we checked if an open-source test system for benchmarking microservices-based systems was used, discussed or proposed. We identified only one such system called Acme Air, which was used and discussed in two different primary studies (P26, P85). Acme Air is a web-based system available in two different architectures (i.e., monolithic service and microservice) and in two different languages (i.e., Node.js and Java), thus providing researchers and practitioners with a very useful benchmark for evaluating, measuring, and comparing their own solutions over a common reference system. Acme Air is publicly available as open-source repository on GitHub.[8]

The lack of practical **systems for benchmarking microservice-based architectures** can severely impact the knowledge transfer from academia to industry. A first step in this direction has been performed with the Acme Air system, which however is still far away from being a realistic benchmarking system. Specifically, it is composed of only six services and all of them are developed using the same programming language and underlying platform; this is rarely the case in real microservice-based systems, for example the Netflix software stack is composed of more than 20 technologies,[9] such as Python, Node.js, Java, React, MySQL, PostgreSQL, Cassandra, and Hadoop. In the near future it will be fundamental for researchers to have a shared, technologically polyglot, open-source benchmarking system that can be used for testing their proposed solutions and for increasing the readiness level of their research products. Technically it is also possible to (semi-) automatically generate large scale systems composed of a large number of heterogeneous microservices; even if a generated system may be realistic only from a syntactical and scale perspective (i.e., its microservices communicate with each other, but they do not do any meaningful operation from a semantic point of view), it may already prove useful for researchers focussing on dependability aspects like scalability, performance, security, availability.

Number of microservices used for evaluation. Most of the primary studies have only used a relatively small number of microservices for their evaluations (i.e., less than 10). Only three primary studies (P82, P35, P72) have used a relatively significant number of microservices using a total of 27, 28 and 67 microservices respectively. In order to put this result into context, a recent industrial survey (Di Francesco et al., 2018) showed that the expected number of microservices deployed after migrating towards the microservices architectural style varies between 5 and 250, with an average of 59. In the future, if the research community on microservice architectures aims to bring new emerging approaches to maturity and perform realistic evaluations, the number of microservices used for evaluation purposes should be increased.

[8] https://github.com/acmeair/acmeair

[9] http://stackshare.io/netflix

6.2. Trend analysis (RQ3)

Fig. 23 summarizes our results for the trend analysis related to RQ2. In particular, we notice interesting trends with respect to *industry involvement* (Fig. 23(b)). Firstly, academic-only publications are increasing at a fast pace since 2014 and publications with both academic and industrial researchers are growing in the last two years as well. Finally, publications with only industrial authors are decreasing, potentially in favour of publications where also academic researchers are involved.

Main findings:

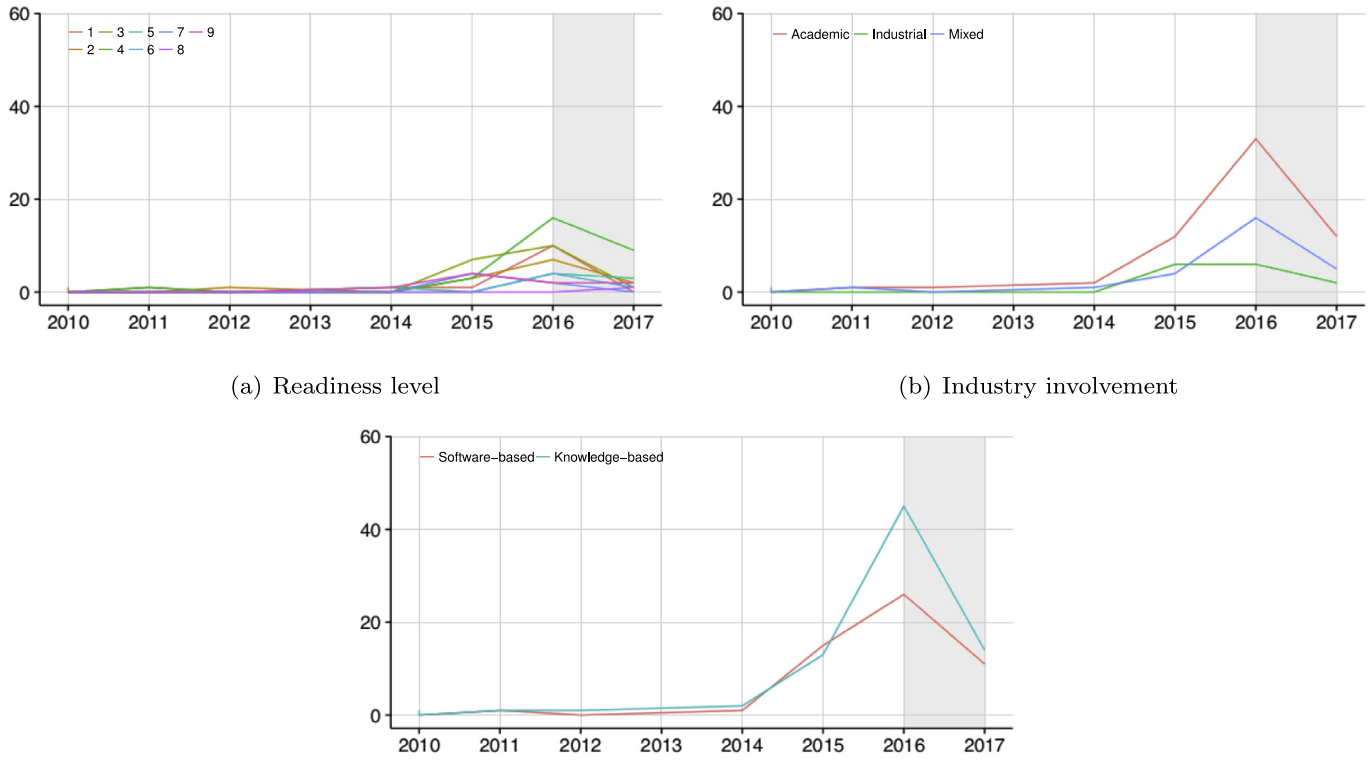
- In spite of their focus on specific solutions, the low TRL scores of most studies suggest that industrial transferability is far away.
- The studies with high TRL are quite heterogeneous, and their contributions range from a component-based gateway middleware (P2), to auto scaling services (P33), to the management of mobile and IoT workloads (P52), etc. All studies with high TRL involve an industrial case study or an application of the proposed solution into on an industrial-scale system.
- The balanced involvement of industrial and academic authors, however, is promising for knowledge co-creation and cross-fertilization.
- The industrial relevance of research evaluations shall be fostered by having more significant open-source test systems or benchmarking applications available.

7. Orthogonal results

Table 2 presents the results of our horizontal analysis.In this phase of the study, we firstly automatically computed a contingency table for every possible pair of parameters of our classification framework. Then, we collaboratively created and discussed a set of 37 potentially relevant insights to be investigated. We iteratively analyzed each potentially relevant insight created in the previous step in order to check if its contingency table actually confirms or disproves its related hypotheses. Finally, we filtered out all the results which were either (i) not supported by a sufficient number of data points, or (ii) chaotic, not revealing any evident pattern. This filtering step was performed manually and collaboratively by three researchers until reaching a full agreement. The full list of potentially interesting relations and the contingency tables for evaluating the actual existence of those relations are available in our replication package (Di Francesco et al., 2017a).

Main findings:

- Gaps for future research especially point toward security and real-time communication in specific areas like IoT and mobile.
- With an eye on quality: (i) many orthogonal results suggest that quality control and security are attracting insufficient research. Given the substantial investments in modernizing software solutions with microservices, this can become a real issue in industrial practice. Also, (ii) the quality attributes *performance* and *maintainability* occur with striking frequency together with various target problems like low flexibility, low efficiency, complexity, and modernization.
- With the pervasive coverage of the design lifecycle phase, a few design patterns seem to consolidate towards a catalogue of solutions ready for reuse by practitioners.



(a) Readiness level

(b) Industry involvement

(c) Tool support

Fig. 23. Trend analysis (RQ3).

- ► Research so far is missing evaluations (maybe hindered by relatively immature technology or lack of representative benchmarks). Not surprisingly, practice confirms a strong interest in migration, and again quality.
- ► History repeats by architectural languages/descriptions focusing on system modeling and neglecting support for analysis/provenance.
- ► Overall, the studies yield a healthy mix of academic and industrial authors, hence suggesting synergies that should help the field to mature toward quality solutions.

8. Threats to validity

In 2015, Petersen et al. (2015) created a checklist for objectively assessing the quality of systematic mapping studies. In this context a score can be computed as the ratio of the number of actions taken in a study versus the total number of actions in the checklist. In our case we achieve a score of 65%, far higher than most systematic studies in the literature, which have a distribution with a median of 33% and 48% as the absolute maximum value. As always, however, threats to validity are unavoidable. The following reports on the main threats to validity of our study and how we mitigated them (Figs. 3–23 and A.1).

External validity. The most severe potential external threat to the validity of our study is on our primary studies not being representative of the state of the art on architecting with microservices. To avoid this to happen, we applied a search strategy consisting of both automatic search and backward-forward snowballing on the selected studies in combination. Specifically, we mitigated the presence of potential gaps left out by the automatic search (which is intrinsically syntactic) by means of the snowballing technique. Indeed, as recommended in the most recent guidelines for systematic studies (Petersen et al., 2015), we extended the coverage of the automatic search by complementing it with a snowballing activity, thus enlarging the set of relevant studies by considering each study selected in the automatic search, and focussing on those papers either citing or cited by it. Also, we considered only peer-reviewed papers and excluded the so-called grey literature (e.g., white papers, editorials, etc.). This potential bias did not impact our study significantly since considered papers have undergone a rigorous peer-review process, which is a well-established requirement for high quality publications. We also applied well-defined and previously validated inclusion and exclusion criteria, which we refined iteratively by considering the pilot studies of our review. Specifically, we thoroughly discussed the definition of each selection criteria in order to have a minimal, but complete set of selection criteria, according to the goal of our study. It is important to note that we decided to have the E2 selection criterion while piloting the search string on the electronic data sources. In that phase, we noticed that a large number of research articles used a very simple example; in those cases, microservices are outside the focus of the proposed research (e.g., approaches for self-adaptive systems which can be applied to any type of system, approaches focussing on REST APIs in general, etc.) and the microservices domain has been used by the authors of the articles in order to contextualize their research contributions in a more recent technology. We added the E2 selection criterion to avoid this phenomenon. Nevertheless, we are aware that the E2 selection criterion could have been risky in case of abuses, so during the application of the selection criteria we have been extremely rigorous and, when in doubt, we went through the full text of the whole study being considered. Moreover, secondary studies have been excluded (criterion E3) because they are meta-studies, and they provide a different perspective about microservices w.r.t. primary studies, which focus more on proposing specific architectural solutions, methods, or

Table 2
Orthogonal results.

Relation	Results
Target problems - Main research areas	When looking at the distribution of main research areas over target problems we notice that *service composition, resources management, low flexibility*, and *complexity* are well covered by all the main research areas. Differently, the least covered problems are: *benchmarking* (only 1 perspective over 7), *low testability* (2/7), *security* (3/7), *real-time communication* (3/7), *low portability* (3/7), and *time to market* (4/7). The research community in software architecture can consider those problems as potential good candidates for contributing in solving not-yet-explored challenges in architecting with microservices. Moreover, some interesting research gaps for the research community on microservice architecture emerged: *security* from the *IoT* perspective, *real-time communication* from the *cloud, IoT* and *mobile* perspectives, *low auditability* from the *IoT* and *mobile* perspectives, and *data management* from the *cloud* perspectives. Those problem-perspective pairs have never been investigated in any of the analyzed primary studies.
Target problems - Readiness levels	There are some problems in which the technology readiness is still leaning towards lower values. These are: *runtime uncertainty, modernization*, and *low portability*. Those problems can be considered as potentially relevant for future researchers as there seems to be a barrier to overcome for architecting with microservices with runtime uncertainty and high portability.
Target problems - Software lifecycle scopes	In general, *design* is the most frequently considered lifecycle phase independently of the considered target problem (the only exception is *low testability* with zero occurrences), followed by *implementation* (only exceptions are *low testability* and *benchmarking* with zero occurrences). During *maintenance* almost all target problems are considered, with no clear interesting trends. *Requirements* are mainly considered when dealing with *low flexibility* problems (11 occurrences), *complexity* (9), *low efficiency* (8), and *modernization* (6). There are target problems which have been considered from a very narrow set of lifecycle phases, like: *low testability* (1/6, *testing*), *benchmarking* (2/6, *design* and *testing*), and *security* (3/6, *design, implementation, operations*). In the future it will be interesting to see if those extremely scoped problems will expand towards a larger number of lifecycle phases, such as requirements, implementation, and maintenance.
Target problems - Quality attributes	The most recurrent pairs of target problems and quality attributes are: *low flexibility* with *performance* (16 occurrences) and *maintainability* (14), *low efficiency* with *performance* (15), *complexity* with *performance* (12) and *maintainability* (13), *service composition* with *performance* (12), *modernization* with *maintainability* (10). The identified pairs show the interdependencies between architectural problems and quality attributes that have been investigated most frequently by the community. Nevertheless, some interesting gaps caught our attention, revealing potentially fruitful research lines for future research on architecting with microservices: (i) *portability* has not been considered when addressing either *low auditability* or *data management*, (ii) *compatibility, portability, reliability*, and *security* have not been considered when addressing *real-time communication*, and (iii) *compatibility, reliability*, and *usability* have not been considered when dealing with *security*.
Quality attributes - Design patterns	Among the most frequently used design patterns we can see that the *API gateway* is benefiting all quality attributes with a spike in *maintainability* (12) and *performance* (9), while *publish/subscribe* is strongly related to the *performance* (7), *maintainability* (7) and *compatibility* (5) quality attributes. The *circuit breaker* pattern is related to *reliability* and *portability* (4), whereas *proxy* is related to *performance* (5). Differently, the *discovery patterns* are related to *maintainability* and *performance* (3). These results can be used by practitioners as a catalogue of prepackaged solutions for gaining better quality of a microservice architecture, as potentially they have been already validated by the research community, or even evaluated in an industrial setting.
Architecting activities - Architecture description types	If on one hand *structural* descriptions cover all the architecting activities, on the other *behavioural* descriptions are only slightly used for describing *reuse* (1 occurrence) of architectural assets (e.g., design elements, decisions, patterns), *getting input* and *providing information* (3). While it is reasonable to consider the activity of reuse more linked to structural concerns of the architecture, it is important to note that missing a behavioural viewpoint can be a strong limitation since it may prevent the architect from reasoning with other stakeholders on the functionalities delivered by the system.
Architectural languages - Architecture provenance	Architectural languages are predominantly used for the *design* of the architecture of the system. Moreover, *informal* architecture descriptions are the only notations used when dealing with *extracted* architectures. This means that architectural languages (like UML) seem to be only used for designing the system, but are neither used for understanding nor analysing the current state of the architecture of the system (i.e., architecture extraction) – in spite of the strong focus on architecture analysis.
Industry involvement - Research contributions	*Industrial* contributions are mainly present in studies contributing with (i) an *application* of architectural methods, principles or tools (17 *academic*, 7 *industrial*, 8 *mixed*) or (ii) a *reference architecture* (1 *academic*, 3 *industrial*, 3 *mixed*). Differently, *academia* is spread in many types of contributions, with the largest difference with respect to industrial contributions in *method* (23 *academic*, 2 *industrial*, 10 *mixed*) and *problem framing* (12 *academic*, 3 *industrial*, 4 *mixed*). This result indicates that the latter types of contributions (i.e., *method* and *problem framing*) are the ones in which industrial participation is missing the most.
Industry involvement - Research strategies	Even though the majority of solution proposals are authored by *academic*-only authors (44/71), an encouraging result is the fact that 19 (out of 71) primary studies have been authored by a *mixed* type of researchers (i.e., both academic and industrial) and 8 (out of 71) by *industrial*-only authors. With the exception of one paper (P70), validation research always involves academic authors (academic-only in 18 occurrences, and mixed in 10 occurrences), which is another encouraging trend since in principle academic researchers can support industrial ones in setting up well-designed, reliable experiments by following known methodological guidelines.

techniques. Nevertheless, even if secondary studies have been excluded because of the E3 exclusion criterion, we considered them in our study for checking the completeness of our set of primary studies, for identifying important issues to be considered in our study, and for defining what is the contribution of our study to the literature.

Internal validity. We rigorously defined our research protocol, and we iteratively defined the classification framework by rigorously applying the keywording process. The synthesis of the collected data has been performed by applying well-assessed descriptive statistics. Also, during the horizontal analysis we made a sanity test of the extracted data by cross-analyzing parameters of the classification framework.

Construct validity. We mitigated this potential bias by automatically searching the studies on multiple data sources, independently of publishers' policies or business concerns; also we are reasonably confident about the construction of the search string since the terms used are very general and suited to our research questions; the automatic search has been complemented with snowballing. Also, we rigorously selected the potentially relevant studies according to well-documented inclusion and exclusion criteria. This selection stage was performed by one researcher and, as suggested in Wohlin et al. (2012), a random sample of potentially relevant studies was identified and the inter-researcher agreement was ensured.

Conclusion validity. We rigorously defined and iteratively refined our classification framework, so that we could reduce potential biases during the data extraction process. In doing so, we also have the guarantee that the data extraction process was aligned with our research questions. More in general, we mitigated potential threats to conclusion validity by applying the best practices coming from three different guidelines on systematic studies (Petersen et al., 2015; Kitchenham and Brereton, 2013; Wohlin et al., 2012). We applied those best practices in each phase of our study and we documented each phase in a publicly available research protocol, thus making our study easy to be checked and replicated by other researchers.

9. Related work

A systematic mapping on microservices was performed by Pahl et al. on a set of 21 primary studies from 2014 to 2015 (Pahl and Jamshidi, 2016). It is a classification of the research directions in the field and highlights the relevant perspectives considered by researchers. Our study differs from Pahl and Jamshidi (2016) as follows: (i) we apply a more comprehensive search process by considering studies published in any year up to 2017, extending their search string, and complementing the automated search with snowballing; (ii) we apply a systematic process for defining a classification framework; (iii) we investigate on the potential of industrial adoption of research in architecting with microservices.

Alshuqayran et al. (2016) presented a systematic mapping study on microservice architecture. Their study focusses on (i) the architectural challenges faced by microservice-based systems, (ii) the architectural diagrams used for representing them, and (iii) the involved quality requirements. Their work and ours can be considered as complementary, both cutting the topic of architecting with microservices from different perspectives. The main difference between the two studies is that ours considers different research questions, thus leading to different results, findings, and implications.

Dragoni et al. (2016) performed an informal survey on microservices. Our study differs from their study because (i) we specifically focus on architectural principles, method, and techniques, rather than on microservices in general; (ii) we apply a rigorous empirical method throughout the study (i.e., systematic mapping), thus providing evidence-based results and easing replication of the performed research; (iii) the objective of our study is to characterize existing research on architecting with microservices, rather than on providing a narrative viewpoint on their historical, current, and future traits.

Kratzke and Quint (2017) conducted a systematic mapping study on cloud-native applications. The main outcome of that study is a clear definition of cloud-native applications, which are defined as "distributed, elastic and horizontal scalable systems composed of (micro)services which isolate state in a minimum of stateful components. The applications and each of their self-contained deployment unit are designed according to cloud-focused design patterns and operated on a self-service elastic platform". Even though the subjects of their study is different from ours (i.e., cloud-native apps vs architecting with microservices), the two studies share the overall goal (building a comprehensive body of knowledge about a topic) and some parameters of the classification framework (e.g., research strategy, quality attributes, publication trends, etc.). Besides the difference in the considered subject, we also investigate on the potential for industrial adoption.

Finally, Bergmayr et al. (2018) conducted a systematic literature review about cloud modeling languages (e.g., TOSCA). The study is motivated by the fact that existing modeling languages for the cloud have different goals, scope, and (partially overlapping) modeling concepts. The main contributions of Bergmayr et al. (2018) are: (i) a common classification for cloud modeling languages, (ii) a comparison framework for cloud modeling languages, and (iii) the elicitation and discussion of a set of relevant findings about the state of the art. Our study differs from the one by Bergmayr et al. because: (i) the focus of our study is on architecting with microservices in general, not only about the modeling aspect, (ii) we focus on microservices, and not on cloud-specific concerns, (iii) our goal is broader and aims at building a map of the state of the art in order to provide an overview of the research area, instead of critically evaluating and interpreting studies on a specific research topic such as cloud modeling languages (Napoleão et al., 2017), (iv) we investigate on the potential of industrial adoption of research contributions, instead of zooming into one specific aspect of each analyzed study.

10. Conclusions

By following the suggestion in Dragoni et al. (2016), the purpose of this study is to provide *a broad survey investigating relationships among research contributions on microservices*. Specifically, we performed a systematic mapping of 103 primary studies and produced a clear overview of the state of the art on architecting with microservices. We have investigated the research on architecting with microservices under three main perspectives: publication trends, focus of research, and potential for industrial adoption. Using the data that we have extracted from the primary studies, we have performed both a vertical and horizontal analyses. Further, we have performed a detailed trend analysis on the data in order to understand how the research on architecting with microservices has been evolving over time.

For each research question, the paper has already summarized (in the boxes titled *Main findings*) the findings we consider the most interesting. In addition, the following reports our key associated reflections.

The scientific interest in microservices exploded in 2015 - hence we expect that the next few years will witness great advances. Our analysis shows that most papers discuss specific solutions and related validation, fact which calls for more fundamental research, reusable practices and lessons learned.

Maybe due this *bottom-up* approach (generalizing from practical solutions), more fundamental principles and claimed benefits have still to be proven. Among them, our analysis of the research focus shows that the quality (and especially performance, functional suitability and maintainability) delivered by microservices architectures is a main research focus, but also yet to be proven; the promised flexibility might come to the cost of a much-higher complexity than expected; and the architecture practices upon which industry can rely are still to be identified.

The pervasive role technology is playing in engineering for, and migrating toward, microservices will hopefully shape some of these architecture practices. For example, the increasing utilization of virtualization and containerization technologies might push microservices in the back-end to address, among others, scalability and elasticity concerns in cloud-based solutions. In a similar vein, the increasing popularity of mobile software might give raise to new microservice-based patterns for the front-end. Both are definitely directions deserving much-needed research.

Finally, investigating the above-mentioned tradeoff between flexibility and complexity calls for intensive synergy between researchers and practitioners, especially because significant microservice-based systems must consist of much larger numbers of microservices than the *toy examples* covered by the publications so far.

Appendix A. Primary studies

Table A.1 reports the full list of the 103 primary studies.

Table A.1
Primary studies.

ID	Title	Authors	Year
P1	A Reference Architecture for Real-time Microservice API Consumption	Cristian Gadea and Mircea Trifan and Dan Ionescu and Bogdan Ionescu	2016
P2	Apache Airavata As a Laboratory: Architecture and Case Study for Component-Based Gateway Middleware	Suresh Marru and Marlon Pierce and Sudhakar Pamidighantam and Chathuri Wimalasena	2015
P3	Synapse: A Microservices Architecture for Heterogeneous-database Web Applications	Nicolas Viennot and Mathias Lécuyer and Jonathan Bell and Roxana Geambasu and Jason Nieh	2015
P4	Emergent Software Services	Nicolas Cardozo	2016
P5	Bifrost: Supporting Continuous Deployment with Automated Enactment of Multi-Phase Live Testing Strategies	Gerald Schermann and Dominik Schoni and Philipp Leitner and Harald C. Gall	2016
P6	Sustaining Runtime Performance While Incrementally Modernizing Transactional Monolithic Software Towards Microservices	Holger Knoche	2016
P7	Case Study: Microservice Evolution and Software Lifecycle of the XSEDE User Portal API	Walter Scarborough and Carrie Arnold and Maytal Dahan	2016
P8	TopoLens: Building a CyberGIS Community Data Service for Enhancing the Usability of High-resolution National Topographic Datasets	Hao Hu and Xingchen Hong and Jeff Terstriep and Yan Y. Liu and Michael P. Finn and Johnathan Rush and Jeffrey Wendel and Shaowen Wang	2016
P9	Service-Oriented Robotic Swarm Systems: Model and Structuring Algorithms	G. Zhou; Y. Zhang; F. Bastani; I. L. Yen	2012
P10	Practical Use of Microservices in Moving Workloads to the Cloud	D. S. Linthicum	2016
P11	Container and Microservice Driven Design for Cloud Infrastructure DevOps	H. Kang; M. Le; S. Tao	2016
P12	Towards Integrating Microservices with Adaptable Enterprise Architecture	J. Bogner; A. Zimmermann	2016
P13	Security-as-a-Service for Microservices-Based Cloud Applications	Y. Sun; S. Nanda; T. Jaeger	2015
P14	TeNOR: Steps towards an orchestration platform for multi-PoP NFV deployment	J. F. Riera; J. Batallé; J. Bonnet; M. Dias; M. McGrath; G. Petralia; F. Liberati; A. Giuseppi; A. Pietrabissa; A. Ceselli; A. Petrini; M. Trubian; P. Papadimitrou; D. Dietrich; A. Ramos; J. Melian; G. Xilouris; A. Kourtis; T. Kourtis; E. K. Markakis	2016
P15	Vendor Malware: Detection Limits and Mitigation	O. Lysne; K. J. Hole; C. Otterstad; O. Ytrehus; R. Aarseth; J. Tellnes	2016
P16	Leveraging microservices architecture by using Docker technology	D. Jaramillo; D. V. Nguyen; R. Smart	2016
P17	Scalable microservice based architecture for enabling DMTF profiles	D. Malavalli; S. Sathappan	2015
P18	The Design and Architecture of Microservices	A. Sill	2016
P19	JMesh – A Scalable Web-Based Platform for Visualization and Mining of Passive Acoustic Data	X. Mouy; P. A. Mouy; D. Hannay; T. Dakin	2015
P20	CYCLOPS: A micro service based approach for dynamic rating, charging & billing for cloud	S. Patanjali; B. Truninger; P. Harsh; T. M. Bohnert	2015
P21	A Reusable Automated Acceptance Testing Architecture for Microservices in Behavior-Driven Development	M. Rahman; J. Gao	2015
P22	Architecture of an interoperable IoT platform based on microservices	T. Vresk; I. Cavrak	2016
P23	Performance Evaluation of Microservices Architectures Using Containers	M. Amaral; J. Polo; D. Carrera; I. Mohomed; M. Unuvar; M. Steinder	2015
P24	A microservices architecture for collaborative document editing enhanced with face recognition	C. Gadea; M. Trifan; D. Ionescu; M. Cordea; B. Ionescu	2016
P25	Gru: An Approach to Introduce Decentralized Autonomic Behavior in Microservices Architectures	L. Florio; E. D. Nitto	2016
P26	Workload characterization for microservices	T. Ueda; T. Nakaike; M. Ohara	2016
P27	Challenges in Delivering Software in the Cloud as Microservices	C. Esposito; A. Castiglione; K. K. R. Choo	2016
P28	Microservice-based architecture for the NRDC	V. D. Le; M. M. Neff; R. V. Stewart; R. Kelley; E. Fritzinger; S. M. Dascalu; F. C. Harris	2015
P29	Microservices approach for the internet of things	B. Butzin; F. Golatowski; D. Timmermann	2016
P30	Towards microservices architecture to transcode videos in the large at low costs	O. Barais; J. Bourcier; Y. D. Bromberg; C. Dion	2016
P31	Distributed Systems of Microservices Using Docker and Serfnode	J. Stubbs; W. Moreira; R. Dooley	2015
P32	Microservice Based Tool Support for Business Process Modelling	S. Alpers; C. Becker; A. Oberweis; T. Schuster	2015
P33	Polyglot Application Auto Scaling Service for Platform as a Service Cloud	S. R. Seelam; P. Dettori; P. Westerink; B. B. Yang	2015
P34	Evaluating the monolithic and the microservice architecture pattern to deploy web applications in the cloud	M. Villamizar; O. Garcés; H. Castro; M. Verano; L. Salamanca; R. Casallas; S. Gil	2015
P35	Swiss TSO integrated operational planning, optimization and ancillary services system	D. Tchoubraev; D. Wiczynski	2015
P36	Experience on a Microservice-Based Reference Architecture for Measurement Systems	M. Vianden; H. Lichter; A. Steffens	2014
P37	Microservices and Their Design Trade-Offs: A Self-Adaptive Roadmap	S. Hassan; R. Bahsoon	2016
P38	Designing a Smart City Internet of Things Platform with Microservice Architecture	A. Krylovskiy; M. Jahn; E. Patti	2015
P39	Open Issues in Scheduling Microservices in the Cloud	M. Fazio; A. Celesti; R. Ranjan; C. Liu; L. Chen; M. Villari	2016
P40	Migrating web applications to clouds with microservice architectures	J. Lin; L. C. Lin; S. Huang	2016
P41	The ENTICE approach to decompose monolithic services into microservices	G. Kecskemeti; A. C. Marosi; A. Kertesz	2016
P42	Gremlin: Systematic Resilience Testing of Microservices	V. Heorhiadi; S. Rajagopalan; H. Jamjoom; M. K. Reiter; V. Sekar	2016
P43	Automated Fault-Tolerance Testing	A. Nagarajan; A. Vaddadi	2016
P44	ClouNS-a Cloud-Native Application Reference Model for Enterprise Architects	Kratzke N., Peinl R.	2016
P45	SeCoS: Web of Things platform based on a microservices architecture and support of time-awareness	Zeiner H., Goller M., Expósito Jiménez V.J., Salmhofer F., Haas W.	2016
P46	Multi cloud deployment with containers	Jambunathan B., Kalpana Y.	2016

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ID	Title	Authors	Year
P47	Micro service cloud computing pattern for next generation networks	Potvin P., Nabaee M., Labeau F., Nguyen K.-K., Cheriet M.	2016
P48	The database-is-the-service pattern for microservice architectures	Messina A., Rizzo R., Storniolo P., Tripiciano M., Urso A.	2016
P49	Service cutter: A systematic approach to service decomposition	Gysel M., Kölbener L., Giersche W., Zimmermann O.	2016
P50	Medley: An event-driven lightweight platform for service composition	Yahia E.B.H., Réveillère L., Bromberg Y.-D., Chevalier R., Cadot A.	2016
P51	Native cloud applications why virtual machines, images and containers miss the point	Leymann F., Fehling C., Wagner S., Wettinger J.	2016
P52	Location and Context-Based Microservices for Mobile and Internet of Things Workloads	Bak P., Melamed R., Moshkovich D., Nardi Y., Ship H., Yaeli A.	2015
P53	An ontology-based reasoning framework for context-aware applications	Anderson C., Suarez I., Xu Y., David K.	2015
P54	A methodology and tool support for widget-based web application development	Nicolaescu P., Klamma R.	2015
P55	Learning-based testing of distributed microservice architectures: Correctness and fault injection	Meinke K., Nycander P.	2015
P56	Microservices validation: Methodology and implementation	Savchenko D., Radchenko G.	2015
P57	Automated Deployment of a Microservice-based Monitoring Infrastructure	Ciuffoletti A.	2015
P58	An ecosystem of user-facing microservices supported by semantic models	Versteden A., Pauwels E., Papantoniou A.	2015
P59	User-aware location management of prosumed micro-services	Klein B., Lopez-De-Ipina D., Guggenmos C., Velasco J.P.	2014
P60	m:Ciudad: Enabling end-user mobile service creation	Davies M., Carrez F., Heinila J., Fensel A., Narganes M., Danado J.C.S.	2011
P61	Curation micro-services: A pipeline metaphor for repositories	Abrams S., Cruse P., Kunze J., Minor D.	2011
P62	Towards a platform for user-generated mobile services	Tacken J., Flake S., Golatowski F., Prüter S., Rust C., Chapko A., Emrich A.	2010
P63	Migrating to Cloud-Native Architectures Using Microservices: An Experience Report	Balalaie, A; Heydarnoori, A; Jamshidi, P	2016
P64	Model-driven Generation of Microservice Architectures for Benchmarking Performance and Resilience Engineering Approaches	Thomas F. Dullmann and Andrévan Hoorn	2017
P65	Towards Effective Virtualization of Intrusion Detection Systems	Nuyun Zhang and Hongda Li and Hongxin Hu and Younghee Park	2017
P66	Publishing Linked Data Through Semantic Microservices Composition	Ivan Salvadori and Alexis Huf and Ronaldo dos Santos Mello and Frank Siqueira	2016
P67	An Architecture to Automate Performance Tests on Microservices	André; de Camargo and Ivan Salvadori and Ronaldo dos Santos Mello and Frank Siqueira	2016
P68	Design and implementation of a decentralized message bus for microservices	Kookarinrat, Pakorn and Temtanapat, Yaowadee	2016
P69	Telecom strategies for service discovery in microservice environments	C. Rotter; J. Illés; G. Nyìri; L. Farkas; G. Csatári; G. Huszty	2017
P70	A VNF-as-a-service design through micro-services disassembling the IMS	A. Boubendir; E. Bertin; N. Simoni	2017
P71	Requirements Reconciliation for Scalable and Secure Microservice (De)composition	M. Ahmadvand; A. Ibrahim	2016
P72	Towards the understanding and evolution of monolithic applications as microservices	D. Escobar; D. Cárdenas; R. Amarillo; E. Castro; K. Garcés; C. Parra; R. Casallas	2016
P73	A scalable routing mechanism for stateful microservices	N. H. Do; T. Van Do; X. Thi Tran; L. Farkas; C. Rotter	2017
P74	A new efficient distributed computing middleware based on cloud micro-services for HPC	F. Z. Benchara; M. Youssfi; O. Bouattane; H. Ouajji	2016
P75	Efficiency Analysis of Provisioning Microservices	H. Khazaei; C. Barna; N. Beigi-Mohammadi; M. Litoiu	2016
P76	A microservice based reference architecture model in the context of enterprise architecture	Yale Yu; H. Silveira; M. Sundaram	2016
P77	Reflections on SOA and Microservices	Z. Xiao; I. Wijegunaratne; X. Qiang	2016
P78	An open IoT framework based on microservices architecture	L. Sun; Y. Li; R. A. Memon	2017
P79	Modelling and Managing Deployment Costs of Microservice-Based Cloud Applications	P. Leitner; J. Cito; E. Stöckli	2016
P80	The evolution of distributed systems towards microservices architecture	T. Salah; M. Jamal Zemerly; Chan Yeob Yeun; M. Al-Qutayri; Y. Al-Hammadi	2016
P81	Microservice Ambients: An Architectural Meta-Modelling Approach for Microservice Granularity	Sara Hassan, Nour Ali, Rami Bahsoon	2017
P82	Workload-Based Clustering of Coherent Feature Sets in Microservice Architectures	Sander Klock, Jan Martijn E. M. Van Der Werf, Jan Pieter Guelen, Slinger Jansen	2017
P83	Microservice Architectures for Scalability, Agility and Reliability in E-Commerce	Wilhelm Hasselbring and Guido Steinacker	2017
P84	Differences Between Model-driven Development of Service-oriented and Microservice Architecture	F. Rademacher, S. Sachweh and A. Zündorf	2017
P85	Towards Recovering the Software Architecture of Microservice-based Systems	G. Granchelli, M. Cardarelli, P. Di Francesco, I. Malavolta, L. Iovino and A. Di Salle	2017
P86	Decision Guidance Models for Microservice Monitoring	S. Haselbock and R. Weinreich.	2017
P87	From monolith to microservices - Lessons learned on an industrial migration to a Web Oriented Architecture	J. Gouigoux and D. Tamzalit	2017
P88	A Dashboard for Microservice Monitoring and Management	B. Mayer and R. Weinreich	2017
P89	Self-managing cloud-native applications: Design, implementation, and experience	Giovanni Toffetti and Sandro Brunner and Martin Blochlinger and Florian Dudouet and Andrew Edmonds	2017
P90	The IPOL demo system: A scalable architecture of microservices for reproducible research	Arévalo M., Escobar C., Monasse P., Monzón N., Colom M.	2017
P91	Microflows: Automated planning and enactment of dynamic workflows comprising semantically-annotated microservices	Oberhauser R.	2017
P92	Continuous software engineering-A microservices architecture perspective	O'Connor R.V., Elger P., Clarke P.M.	2017
P93	A microservice architecture for the Intranet of Things and energy in smart buildings	Bao K., Mauser I., Kochanneck S., Xu H., Schmeck H.	2016
P94	Domain Driven Design and Provision of Micro-services to build Emerging Learning Systems	Khemaja M.	2016
P95	Cloudware: An emerging software paradigm for cloud computing	D. Guo; W. Wang; G. Zeng; Z. Wei	2016
P96	MORe: A micro-service oriented aggregator	Gavrilis D., Nomikos V., Kravvaritis K., Angelis S., Papatheodorou C., Constantopoulos P.	2016
P97	Incremental integration of microservices in cloud applications	Zuniga-Prieto, Miguel and Insfran, Emilio and Abrahao, Silvia and Cano-Genoves, Carlos	2016

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P98	Trident: Scalable compute archives: Workflows, visualization, and analysis	Gopu A., Hayashi S., Young M.D., Kotulla R., Henschel R., Harbeck D.	2016
P99	A Service-Oriented Approach to Crowdsensing for Accessible Smart Mobility Scenarios	Mirri S., Prandi C., Salomoni P., Callegati F., Melis A., Prandini M.	2016
P100	On micro-services architecture	Namiot, Dmitry and Sneps-Sneppe, Manfred	2014
P101	Towards a Technique for Extracting Microservices from Monolithic Enterprise Systems	Levcovitz, Alessandra and Terra, Ricardo and Valente, Marco Tulio	2016
P102	A dynamic deployment method of micro service oriented to SLA	ZL Ji, Y Liu	2016
P103	InterSCity: A Scalable Microservice-based Open Source Platform for Smart Cities	Arthur de M. Del Esposte, Fabio Kon, Fabio M. Costa and Nelson Lago	2017

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