Microservice security: a systematic literature review

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Microservices is an emerging paradigm for developing distributed systems. With their widespread adoption, more and more work investigated the relation between microservices and security. Alas, the literature on this subject does not form a well-defined corpus: it is spread over many venues and composed of contributions mainly addressing specific scenarios or needs. In this work, we conduct a systematic review of the field, gathering 290 relevant publications—at the time of writing, the largest curated dataset on the topic. We analyse our dataset along two lines: a) quantitatively, through publication metadata, which allows us to chart publication outlets, communities, approaches, and tackled issues; b) qualitatively, through 20 research questions used to provide an aggregated overview of the literature and to spot gaps left open. We summarise our analyses in the conclusion in the form of a call for action to address the main open challenges.

Microservice Security: A Systematic Literature Review

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ABSTRACT

Microservices is an emerging paradigm for developing distributed systems that is rapidly approaching widespread adoption. In response to this adoption, an increasing body of work has investigated the relation between microservices and security. Unfortunately, the literature on this subject does not form a well-defined corpus: it is spread over many venues, and it consists of contributions that mainly address specific scenarios or needs. In this work, we conduct a systematic review of the field, gathering 290 relevant publications—at the time of writing, the largest curated dataset on the topic. We analyse our dataset through (i) publication metadata, which allows us to chart publication outlets, communities, approaches, and tackled issues; and (ii) through 20 research questions, which we use to provide an aggregated overview of the literature and to identify gaps left open. Our study leads to a call for action to address the main open challenges.

1 INTRODUCTION

Microservices is an emerging development paradigm, where software is built as a composition of multiple services (the "microservices"). Each microservice implements the business logic of a component of the application and is independently executable and deployable. Microservices interact with each other via message-passing APIs (Dragoni et al., 2017).

Over the last 6 years, microservices have become a popular topic and one of the go-to approaches for many cloud computing projects. According to Web of Science, more than 1000 articles about microservices have been published since 2014. The year 2020 accounts for more than 400 of them, which points out that interest in the topic is still rising. Microservices are popular because they bring substantial advantages with respect to scalability in cloud environments and flexibility in the process of software development. By separating application components as independent services, software designers can specialise each component by using a dedicated technology and then integrate all such heterogeneous components via technology-agnostic APIs.

Alas, the advantages of microservices come at a cost: distributed systems are hard to manage, and increasing the number of services of an application gives malicious actors a larger attack surface (Dragoni et al., 2017). Several security concerns that are particularly relevant for microservices have been identified by Chandramouli (2019), and early research has already shown that the application of standard patterns for system reliability needs to take new parameters into consideration—like the locations at which the patterns are deployed (Montesi and Weber, 2018).

The importance of security in microservices creates the need for understanding and analysing the state of the art for securing this kind of architectures. It is particularly important to understand which problems are especially relevant for microservice systems, and how existing techniques can contribute to addressing them. However, there is still a lack of systematic investigations of studies at the intersection of security and microservice architectures.

Here, we aim to fill that gap by presenting a systematic review of the state of the art of microservice security. We followed a structured approach, which led us to select and gather 290 peer-reviewed publications. At the time of this writing, this constitutes the largest curated dataset on the topic. We first perform a quantitative analysis on the metadata of the publications,

for example, publication outlets and keywords. This provides insight into the communities and key research concepts that currently characterise the field. We then map each publication to a vector of 20 different markers, corresponding to 20 research questions on microservices security that we formulated based on established security techniques and the field of microservices as a whole.

Our research questions focused on threat models, security approaches, infrastructure, and development approach. We perform correlation analysis to show that our questions are well-posed (independence), and also to confirm that some topics correlate positively (e.g., Intrusion Detection and Intrusion Prevention, and Agile Development and DevOps as well). Findings from our analysis include: issues with technology transfer from academia to industry on microservices security; lack of guidelines for adopting security by design in microservices; lack of appropriate threat models; lack of guidelines for addressing the attack surface given by technology heterogeneity; and security issues when migrating systems to microservices. Our data, findings, and discussions form a useful basis for orienting future developments of the field.

In summary, the main contributions of this work are:

- the characterisation of Microservices Security as an early-stage, growing research field in need of systematisation and more mature contributions (Section 5.1.1, Section 5.2.1);

- the identification of the main research communities on the Microservice Security field and the clustering of authors (Section 5.1.2);

- a presentation of the trends of the main security attacks involving microservice architectures, both from the points of view of threat model (Section 5.2.2) and mitigation (Section 5.2.3);

- a report on the current infrastructural security solutions for microservices (Section 5.2.4) as well as the interaction between the main microservices development approaches (such as DevOps and Agile) and security (Section 5.2.5);

- a correlation analysis of the answers to our research questions in papers, which sheds light on relationships among the different aspects of microsrevice security (Section 5.2.7);

- a summary of the main open challenges that emerged from our study, which form a call for action for the community of researchers and practitioners working in the field of microservice security (Section 6).

Structure of the article   We start by providing a summary of related work in Section 2. In Section 3 and Section 4 we detail the method we followed to conduct the systematic literature review and the research questions, respectively. We present our results in Section 5 and we conclude in Section 6 with a discussion on the outstanding challenges.

2 RELATED WORK

To the best of our knowledge, the published works that are closest to ours are those by Vale et al. (2019) and Almeida et al. (2017). Vale et al. (2019) present a systematic mapping that identifies the security mechanisms used in microservice-based systems. Contrary to our work, which provides a general overview on the state of the art of microservices security, the authors narrow their focus on cataloguing the security technologies and mechanisms adopted by developers of microservice-based systems—e.g., authentication and authorisation—leaving out other subjects related to security, like threat models and development methods. Similarly to Vale et al., Almeida et al. (2017) concentrate on surveying the technologies and standards for security, privacy, and communication used in the area of microservice architectures in the cloud.

Extending our view to articles that, at the time of this writing, are not available as peer-reviewed publications, we mention the work by Hannousse and Yahiouche (2020) and Ponce et al. (2021). Hannousse and Yahiouche (2020) present a systematic categorisation of threats on microservice architectures and propose a selection of possible mitigations. Ponce et al. (2021) look at how "security smells" affect microservice-based applications and how to mitigate the effects of such smells through refactoring. As for the proposals by Vale et al. and Almeida

et al., the difference between our work and Hannousse and Yahiouche (2020) lies on generality: Hannousse and Yahiouche narrow their investigation down to the threats identified in the literature. Similarly, the work of Ponce et al. (2021) focuses on the programming of microservices.

In addition to the related work discussed above, there are quite a few neighbouring surveys with respect to our work that are interesting to discuss: while these studies are not dedicated to the topic of microservice security, they explicitly mention security as an important concern for microservices in different contexts—software engineering, Internet of Things, containerisation, etc. The purpose of reviewing neighbouring related work is twofold:

1. It shows the multifaceted nature of microservice security, giving concrete evidence of the need for an investigation which is both wider and deeper, as we do in this work.

2. It provides a general overview of the challenges and possible uncovered research topics related to security in microservices—which inspired some of the questions presented in Section 3.

Dragoni et al. (2017) present an overview of microservices, including a discussion of the origins of the paradigm, its state of the art, and future challenges. They identify a number of trust and security challenges posed by the paradigm. We mention a few examples. Service reuse, one of the key benefits pushed for in the microservice paradigm, requires adopting secure mechanisms for service authentication and authorisation. The increased granularity and heterogeneity of microservice architectures extends considerably the attack surface of these systems. The sophisticated DevOps infrastructure required to operate microservices effectively is a new attack vector.

Garriga (2017) conducted a preliminary analysis toward a taxonomy of microservices architectures. While not addressing in particular security concerns, Garriga reports that the security subject is not extensively addressed, highlighting how monitoring and microservice communication trust chains should receive particular attention.

Joseph and Chandrasekaran (2019) reviewed approaches proposed in the literature to deal with the various concerns of microservice-based systems. The authors mention the large attack area offered by microservices subject to insider/privilege-escalation attacks and network security issues.

Casale et al. (2016) surveyed the topics of European research projects in the area of software engineering. Regarding microservices security, they highlight four main challenges: increasing the usage of software validation and verification methods; improving the trust and interoperability of services through (self/federated)-certification of outputs based on standards; adopting a security-by-design approach on the whole software lifecycle; and helping developers with addressing discontinuities in the chain of compositionality between services and execution environments—e.g., due to data leakages derived from fragile container-host interactions.

Lichtenthäler et al. (2019) investigate and discuss the challenges of migrating monoliths to microservices. They observe that security should be part of the migration planning phase to begin with, and that developers need models and frameworks to help them elicit, track, and manage the (frequently implicit) assumptions and invariants induced by the migration of the legacy system. These observations are shared with Di Francesco et al. (2017), who suggest that the microservice architectural style has a direct impact on the design of a system and that researchers are still investigating how to leverage its characteristics with respect to system quality and security. Di Francesco et al. note that there exists uncertainty about the realisation of microservices, indicating the need for comprehensive references to help programmers in the multifaceted aspects of microservice development.

Noura et al. (2019) address the open challenges of interoperability in the Internet of Things (IoT), noting how microservices can constitute a solution for the programming of highly distributed IoT networks and provide two decades worth of research and industrial experience to tackle interoperability in heterogeneous systems. Regarding the general security of IoT systems, Noura et al. note the emergence of security issues (e.g., authentication and access control) when system design permits direct access to resource-constrained devices. Reviewing the many solutions and levels at which IoT interoperability can be tackled, Noura et al. note the challenge of

both maintaining and guaranteeing the same level of security when mediating among different technologies.

Márquez and Astudillo (2019) examine microservice availability tactics to detect, prevent, mitigate, and recover from faults. They highlight how the tactics for the availability of microservices mainly focus on preventing faults, whereas detection, reaction, and recovery are scarcely addressed. Commenting on related challenges, Márquez and Astudillo report a deficit of solutions to support the restoration of normal functionalities after a microservice architecture suffered from some faults.

Ahmed et al. (2019) surveyed robust and flexible service management platforms for IoT systems. Like Noura et al., they identify microservice architectures as the most suitable architectural pattern to handle the heterogeneity of IoT systems and that the foremost challenge in the field is the robust integration of different technologies. Ahmed et al. also report how conventional security solutions and practices are not suitable to handle the expansion, mobility, resource constraints, and new security requirements of the considered systems.

Cerny and Donahoo (2016) investigate service integration from the perspective of separation of concerns and identify problems with conventional service integration design/technologies. They report that the lack of proper cross-cutting concerns in programming technologies make it difficult to capture and guarantee that invariants of a given microservices—specifically, on security—hold when paired with integration components.

Yang et al. (2014) survey how cloud computing systems can help scientific research. In their report, they notice how the (micro)service paradigm is useful to make resources available to collaborating researchers by providing a well-defined interface specifying the operations that can be performed on, or with, a given resource. However, they also report that privacy and trust issues are of particular concern to researchers, especially in fields that are processing sensitive data such as medical research. For this, appropriate provenance metadata is required, both to understand how and by whom the data was created and modified, as well as to understand where it has been potentially exposed to corruption. Similar comments are shared also by Plaza et al. (2018) in the context of healthcare cyber-physical systems. In particular, proper encryption is reported as a key component for (real-time) data acquisition.

Soldani et al. (2018), reviewing the "pains and gains" of microservices in the grey literature, found how security generates pains at design-time. Like Yang et al. (2014), Soldani et al. comment that microservice-based applications should support the consistent determination of the provenance and authenticity of data, noting the paradox of that being in contrast with the heavily-distributed nature of microservice systems. Another (meta)observation by Soldani et al. is how there is a gap between the industrial understanding and state-of-practice on microservices and the state-of-the-art of academic research, one possible reason being that academics have limited access to industrial-scale microservice-based applications.

Di Francesco et al. (2019) identify, classify, and evaluate the state of the art on architecting with microservices from the perspectives of publication trends, the focus of research, and potential for industrial adoption. On security, they report that it is attracting insufficient research. The works by Vural et al. (2017) and Alshuqayran et al. (2016) follow similar modalities and results.

Bélair et al. (2019) surveyed security of containers, a technology frequently paired with microservices. They report how container security is still in an early phase and it faces unsolved challenges. The results presented by Bélair et al. match those by Sultan et al. (2019), who report the presence of a large number of challenges linked to containerisation because OS kernel sharing introduces security issues absent from virtualisation solutions. Sultan et al. also highlight the importance of enhancing vulnerability management, digital investigation, and container alternatives.

Puliafito et al. (2019) present a survey on the employment of fog computing to support IoT devices and (micro)services. In their study, they report how security is the largest cross-cutting technical concern within critical IoT systems, which necessitates a common baseline and interoperable standards to address security challenges within both hardware and software. In particular, Puliafito et al. advocate for solutions to provide a full-stack secure chain of trust from devices to fog/cloud components, which has been only preliminary explored (as remote attestation techniques). Trnka et al. (2018) and Puliafito et al. report also the importance of

Publication	Year	Type	Num.	White L.	Grey L.	Sources
This work	2021	SLR	290	●	○	ACM Digital Library IEEE Xplorer SpringerLink Scopus Science Direct Wiley Google Scholar
Vale et al.	2019	SLR	26	●	○	ACM Digital Library IEEE Xplorer SpringerLink Science Direct Wiley Google Scholar
Almeida et al.	2017	Survey	N.A.	●	○	N.A.
Hannousse and Yahiouche	2020	SLR	46	●	○	ACM Digital Library IEEE Xplorer SpringerLink Science Direct Wiley
Soldani et al.	2018	SLR	51	○	●	Google Bing Duck Duck Go Yahoo! Webopedia

Table 1. Summary table and comparison with related works. For each row/work in the table, we report: its reference; its publication year; its type (systematic literature review (SLR), survey, etc.); the number of publications it encompasses; whether it analyses white (peer reviewed) literature; whether it analyses grey (blog posts, etc) literature; the sources it used to search its dataset.

addressing the concerns of context-aware security (in IoT systems), especially for authentication and authorisation.

Also Yu et al. (2019) surveyed the literature on microservice-based fog applications to elicit the security risks threatening them. The main threats highlighted include: kernel-level leakage vulnerabilities linked to containerised deployment; man-in-the-middle/insider attacks on data-transmission interception; the need to verify when services become compromised/misbehave; and network-level vulnerabilities on data-routing alteration.

The table 1, shows the differences between these various works, in numerical and boolean terms. As clearly evincible, our work expands the previous works by adding a conspicuous amount of analysed publications; using white literature at its roots and following the trend and methods of the main Systematic White Literature Reviews.

3 REVIEW METHOD

In this section, we describe and motivate the steps we followed to perform our systematic review.

Following the guidelines by Snyder (2019), and as depicted in Fig. 1, we started by searching and retrieving the literature for relevant publications from several data sources by using the same keyword query. We then performed a manual revision process of the automatically selected publications to exclude publications out of the scope of this study and perform snowballing—i.e., recursively adding to the dataset relevant publications cited by the already selected publications. The resulting dataset consists of 290 publications. We analysed these publications to collect statistical and transparent answers to our research questions, which are detailed in Section 4.[1]

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[1]The list of the publications and their bibliography information is publicly available at https://doi.org/10.5281/zenodo.4774894.
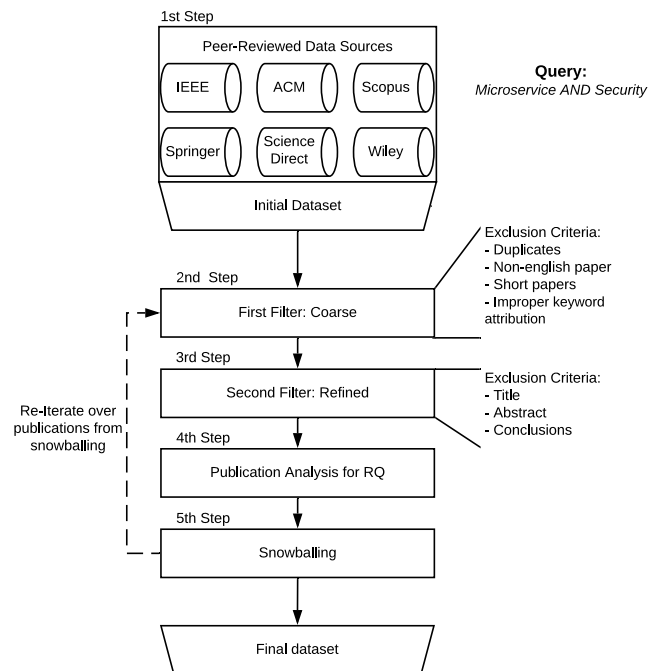
Figure 1. Schema of the method followed to gather the dataset for this review.

3.1 Selection Query and Collection of Publications

Security in microservices includes complex and heterogeneous topics, ranging from development to infrastructural concerns. In our choice of a selection query to gather an initial dataset, it was important to pick a sufficiently general query. For this reason, we adopted the query "Microservice AND Security" for our initial search, capturing all the publications containing both terms in any of their title, abstract, or body.[2]

Di Francesco et al. (2019); Plaza et al. (2018); Soldani et al. (2018) reported how publications on the topic of Microservice started in 2014. Taking into account this fact, we limited our research to contributions published since 2014. During the seven years covered by our work, the body of knowledge on this topic has grown significantly. For this reason, we deemed it useful to consider white literature only: in terms of quantity, it represents a very meaningful sample of the research produced during the considered time frame, and in terms of quality, it allowed us to rely on peer review. Thanks to the more uniform organisation of white literature, we are also more confident in the level of consistency of our choice and application of the selection criteria. This is not to say that grey literature is not worth investigating. Blog posts, personal websites, technical reports, white papers, etc., are often the preferred venues for practitioners to share ideas. However, as also pointed out in Soldani (2019), "it is very difficult to uniquely measure the quality of grey literature when conducting a systematic, controllable, and replicable secondary study" and we are not aware of a standard method for the evaluation of grey literature. Analysing the grey literature was beyond the quality goal of this article and we leave it as future work.

Accordingly to this strategy, we collected publications from 6 different publishers, focusing on peer-reviewed publications. We did not, for example, use Google Scholar or arXiv, since they also list resources that are not peer-reviewed. We list the publishers, reporting the respective numbers of publications that matched our query:

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[2]We performed experiments with potentially more inclusive queries, such as "Microservice AND (Security OR Authorisation)", as well. The tried queries, however, did not extend the search in any useful way since the term "Security" proved to be general enough to cover specialised aspects like authentication, authorisation, and (safe) communication.

240 • ACM (`https://dl.acm.org/`), 478 publications;

241 • IEEE explore (`https://ieeexplore.ieee.org/`), 181 publications;

242 • Springer (`https://link.springer.com/`), 345 publications;

243 • Scopus (`https://www.scopus.com/home.uri`), 134 publications;

244 • Science Direct (`https://www.sciencedirect.com/`), 358 publications;

245 • Wiley (`https://onlinelibrary.wiley.com/`), 208 publications.

246 This gave us an initial dataset of 1704 publications in total. We collected publications published
247 up to the 31st of December 2020, using the academic subscriptions provided by the affiliations of
248 the authors—the University of Bologna and the University of Southern Denmark. To guarantee
249 the same level of trustworthiness and authenticity, we retrieved the publications only from the
250 official entries avoiding external sources such as the authors' personal websites.

3.2 Publications Triage

252 The publications retrieved from the publishers were processed in three steps to check if they
253 should be excluded according to distinct exclusion criteria. Graphically, in Fig. 1, these steps are
254 labelled as 2nd, 3rd, and 4th Step(s).

255 In the 2nd Step, we looked at whether the keywords "Microservice" and "Security" were
256 used. We excluded a publication if the keywords appeared only in the bibliography. Moreover,
257 we excluded the publication if it was too short (less than two pages), publications not written in
258 English, and duplicate publications already listed in another publisher source.

259 In the 3rd Step, we looked at the title, abstract, and conclusion of each publication. Publica-
260 tions that do not treat or discuss topics related to microservices and security were excluded. In
261 this step, we also excluded publications in which the security topic was orthogonal or incidental.
262 In this way, we excluded publications where "microservices and security" was one of the possible
263 application scenarios, but not the main subject of the study. We also excluded cases in which
264 the work tangentially mentioned the satisfaction of some security aspects, without detailing
265 the design/development of the security technologies to accomplish them. For example, we
266 excluded publications focusing on blockchain technologies where the authors incidentally men-
267 tion authentication and integrity protection as inherent security properties of blockchain-based
268 implementations.

269 In the 4th Step, we performed an analysis of the publications, answering to the research
270 questions (RQ) detailed in Section 4. No publications were excluded at this step.

271 At this point, the following publications remained in the dataset (268 in total):

272 • ACM, 67 publications;

273 • IEEE explore, 59 publications;

274 • Springer, 46 publications;

275 • Scopus, 28 publications;

276 • Science Direct, 53 publications;

277 • Wiley, 15 publications.

3.3 Snowballing

279 As the last (5th) step for the systematic literature review, we performed a backward snowballing
280 process (Wohlin, 2014) with the objective of identifying additional relevant references for our
281 study from the works cited by the already selected publications.

282 All references collected in this way underwent the triage by following the Steps 2, 3, and
283 4. Each referenced publication accepted for inclusion by these steps was then added to the
284 dataset of selected publications. Snowballing was recursively performed on these newly-added
285 publications until reaching a fixed point; i.e., until no new publications was added to the dataset.

286 The outcome of repeatedly applying the snowballing process led to the following results:

- 40 references in the first round, from which we selected 9 publications;

- 22 references in the second round, from which we selected 8 publications;

- 5 references in the third round, from which we selected 5 publications;

- 4 references in the fourth round, where we selected 0 publications.

The 4 cycles of snowballing yielded 22 additional publications that were included in the dataset to reach the final size of 290 publications.

4 RESEARCH QUESTIONS

In this section, we detail the research questions that guided our systematic review.

Usually, the research questions for systematic literature reviews are fairly broad and do not amount to more than six. In our case, we chose to adopt more questions (20) but dichotomous (i.e., with yes-or-no answers), to favour precision and objectiveness. To define the questions and seek guidance in categorising the relevant security issues for microservices, we took inspiration from the related work presented Section 2, as well as from the state of the art in standards and methods, namely the NIST Special Publication 800-204 "Security Strategies for Microservice-based Application Systems" (Chandramouli, 2019).

Our questions are collected in four macro groups (**G**s), each covering a different concern.

- **G1:** Threat Model. Questions on threat modelling and how threats are dealt with.

- **G2:** Security Approach. Questions on the security approach, e.g., whether it is preventive, adaptive, proactive, or reactive.

- **G3:** Infrastructure. Questions on the infrastructure that microservices run on.

- **G4:** Development. Questions on the development process.

The questions in each group are reported in the remainder of this section.

4.1 First group: Threat Model

Mapping the usage of threat models is important to see gaps when a security violation must be handled, or if known models are outdated and need to be adjusted. The NIST report, for instance, hints at the importance of identifying the threats looming over a microservices architecture (Chandramouli, 2019). The usage of a formal threat model has proven to be extremely useful in the identification of attack types and their strategic countermeasures (Death, 2017).

Several threat models exist in the literature. The most famous one is STRIDE (Kohnfelder and Garg, 1999) named after the Spoofing, Tampering, Repudiation, Information Disclosure, Denial of Service, and Elevation of privilege security threats. Other threat models however exists, such as PASTA (UcedaVelez and Morana, 2015) or OWASP (OWASP Foundation, 2020).

In our review and with this first group of questions, we aimed to understand whether a publication followed a known model, strategy, or guideline. Alternatively, we wanted to know if new security models were proposed.

This group consists of the following questions.

- **Q1:** Does the publication mention STRIDE, or at least consider all of its aspects?

- **Q2:** Even without explicitly mentioning STRIDE, does the publication involve at least one of its aspects (Spoofing, Tampering, ...)?

- **Q3:** If STRIDE aspects or equivalent are considered, does the publication propose/discuss a concrete implementation/solution (either developed by the same author or one taken from the literature)?

- **Q4:** Does the publication consider or follow another threat model rather than STRIDE without introducing a new one?

332   • **Q5:** Does the publication mention policies, workflows, or guidelines to handle violations?

333   In particular, with question Q1 and Q3 we looked for the adoption of STRIDE, being the
334 most popular threat model. In the remaining questions, we investigate if the publication defined
335 some threat model—either from the literature or a newly one introduced in that publication—or
336 at least discussed equivalent principles or guidelines without mentioning STRIDE.

4.2 Second Group: Security Approach

338 Many related works cite the usage of preventive measures to secure microservices (Márquez
339 and Astudillo, 2019; Vale et al., 2019; Garriga, 2017; Almeida et al., 2017; Ahmed et al., 2019;
340 Soldani et al., 2018) while some indicate the need for further research in the other directions
341 of proaction, reaction, and adaptation (Vale et al., 2019; Márquez and Astudillo, 2019). With
342 this second block of questions, we wanted to go deeper into the security aspects, considering the
343 specific security approaches, solutions, and also the role that microservices play.

344   This group consists of the following questions.

345   • **Q6:** Does the publication mention Intrusion Detection System (IDS) functionalities?

346   • **Q7:** Does the publication mention Intrusion Prevention Systems (IPS) functionalities?

347   • **Q8:** Does the publication mention Threat Intelligence?

348   • **Q9:** Does the publication mention Exfiltration Leaks?

349   • **Q10:** Does the publication address Insider Threats?

350   • **Q11:** Are microservices part of the solution?

351   • **Q12:** Are privacy and GDPR considered?

4.3 Third Group: Infrastructure

353 The NIST report by Chandramouli (2019) dedicates a large part of its content to infrastructural
354 security solutions for microservices. Similarly, the majority of the mentioned related work in
355 Section 2 presents or at least cites infrastructural solutions for security, acknowledging that the
356 infrastructure of microservice systems is typically complex, encompassing concerns that span
357 from service deployment and service-to-service coordination (discovery, composition, consistency)
358 to the definition of security-specific mechanisms (authorisation, authentication).

359   In this group of questions, we aimed at finding information on the infrastructure configurations
360 considered in the publication. This group consists of the following questions.

361   • **Q13:** Does the publication specify how the proposed architecture is controlled or managed
362   (e.g., in a centralised, decentralised, or hybrid way)?

363   • **Q14:** Does the publication mention Infrastructure-as-a-Service?

364   • **Q15:** Does the publication mention service discovery?

4.4 Fourth Group: Development

366 Microservices are often associated with software development practices like DevOps and Ag-
367 ile (Balalaie et al., 2016; Vadapalli, 2018) which, in turn, are heavily influenced by the inclusion
368 of security-oriented practices (Casale et al., 2016; Lichtenthäler et al., 2019; Cerny and Donahoo,
369 2016; Soldani et al., 2018).

370   In this last set of questions, we aimed at checking the extent to which these practices are used
371 also in the setting of security, for example by verifying whether specific development processes
372 and security standards are considered.

373   This group consists of the following questions.

374   • **Q16:** Does the publication mention DevOps, Continuous Integration, Continuous Deploy-
375   ment, or Continuous Delivery?
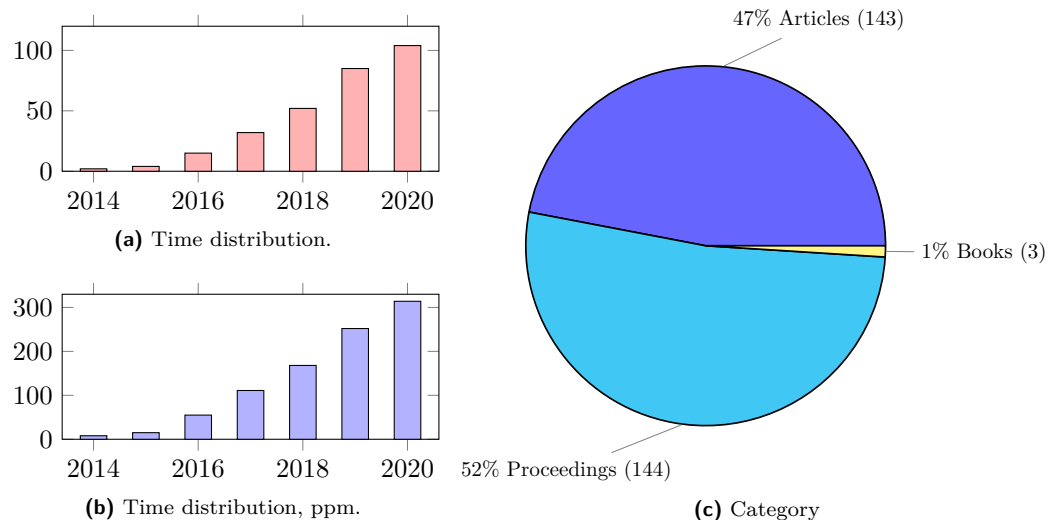
Figure 2. Time and category distribution of publications.

- **Q17:** Does the publication mention Agile, or how security experts are integrated from a development process point of view?

- **Q18:** Does the publication mention Domain Driven Development?

- **Q19:** Does the publication mention Model Driven Development?

- **Q20:** Does the publication mention certifications, such as ISO27000[3], or technological standards such as X.509[4]?

5 REVIEW RESULTS

In this section, we present the outcome of the literature review. We start by presenting quantitative results obtained from the metadata of the publications in our dataset. This is useful to map the trends over time and the current shape of the field, in terms of the number of contributions, type (proceedings, articles), communities, and keywords (and their relations). Then, we present results derived from the analysis of the types of contributions (theoretical, applicative, etc.) and of the relation between the selected dataset and our research questions (cf. Section 4). This part is aimed at providing a detailed insight on existing research patterns, gaps, and uncovered areas of the field. We close the subsection with a correlation analysis of the questions, providing a quantitative look over the relationships between them. For reference, we also report our dataset in tabular form, where each entry is associated with the positive answers given to our research questions.

> **Insights**
>
> In the following subsections, we highlight in boxes (like this one) the main insights that emerge from our analysis. Each insight motivates an open challenge, which we write in bold as the heading of the insight. We will use these challenges in Section 6 to structure our discussion about useful future directions for research on microservice security.

5.1 Metadata analysis

We start our quantitative analysis of the collected dataset by presenting in Fig. 2(a) the time distribution of the selected publications. As expected, security in microservice systems gained a

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[3]https://www.iso.org/isoiec-27001-information-security.html
[4]https://tools.ietf.org/html/rfc5280

Acronym	Name	# in dataset
ARES	International Conference on Availability, Reliability and Security	2
CCGRID	IEEE/ACM International Symposium on Cluster, Cloud and Internet Computing	2
EuroS&P	European Symposium on Security and Privacy	2
ICSA	IEEE International Conference on Software Architecture	3
IFIP	The International Federation for Information Processing Conference	3
MEDES	ACM Conference on Management of Digital EcoSystems	2
NOMS	Network Operations and Management Symposium	2
SEC	Security Conference	3
STAF	Software Technologies: Applications and Foundations Interoperable Systems	2

Figure 3. Conferences with the largest number of publications in our dataset.

398 lot of academic interest in the latest years. This is reflected by the sharp increase in the number
399 of publications since 2014. In Fig. 2(a), we report the number of collected publications per year.
400 As a reference to indicate the degree of growth of the field, we report in Fig. 2(b) the yearly ratio
401 (in parts per million) between the collected publications and the overall number of publications
402 in computer science[5].

5.1.1 Publication Outlets

404 From the plot in Fig. 2(c) we see that conferences and journal venues are the most common
405 outlets, while books/collections are underrepresented. This last fact indicates the early stage
406 of the field, where established references are still lacking. However, conference proceedings are
407 almost matched by journal articles, marking a maturing trend of results that are solid enough to
408 constitute material for more structured contributions, as those found in peer-reviewed journals.

409 We now concentrate on the specific conferences and journals where the publications in our
410 dataset have been published. In Figs. 3 and 4, we report this result in two versions: *i*) in tabular
411 form, on the left-hand side of Figs. 3 and 4, with the acronym, the full name, and the number of
412 contributions in our dataset of the venues with the most contributions and *ii*) on the right-hand
413 side of Figs. 3 and 4, showing the data on the left as a pie chart.

414 Regarding the distribution of publications over the different categories of venues, we note
415 how the audience of journals and conferences vary. In fact, there is no predominance of security-
416 oriented or even software engineering venues, which could have been the most likely targets.
417 Instead, the analysed publications appear at venues addressing a broad range of topics, from
418 networking to cloud computing, and on open journals such as IEEE Access and ACM Queue.
419 Furthermore, there is no clear preferred venue that dominates the others, but contributors are
420 rather scattered over many neighbouring venues.

421 We give a twofold interpretation of the phenomenon. On the one hand, this fact can indicate
422 that microservice security is perceived as of cross-disciplinary interest, each contribution seeing
423 it from the lens of its specific area (whether it be software engineering, networks, sensors,
424 cloud computing, etc.). On the other hand, we notice the lack of specific venues dedicated to
425 microservices, and least of all, dedicated to microservice security.

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[5]Source: https://dblp.org/statistics/publicationsperyear.html.

Acronym	Name	# in dataset
CC	Cluster Computing	4
CCPE	Concurrency and Computation: Practice and Experience	4
ESE	Empirical Software Engineering	2
FGCS	Future Generation Computer Systems Conference	7
FI	Future Internet	2
IEEE Access	IEEE Access Multidisciplinary open access journal	5
IEEE IC	IEEE Internet Computing	3
IEEE PDS	IEEE Transactions on Parallel and Distributed Systems	3
IST	Information and Software Technology	2
JSS	Journal of Systems and Software	8
MNA	Mobile Networks and Applications	2
MTA	Multimedia Tools and Applications	2
PCS	Procedia Computer Science	3
Queue	ACM Queue	3
SICS	Software-Intensive Cyber-Physical Systems	2
SPE	Software: Practice and Experience	4
Sensors	IEEE Sensors Journal	3
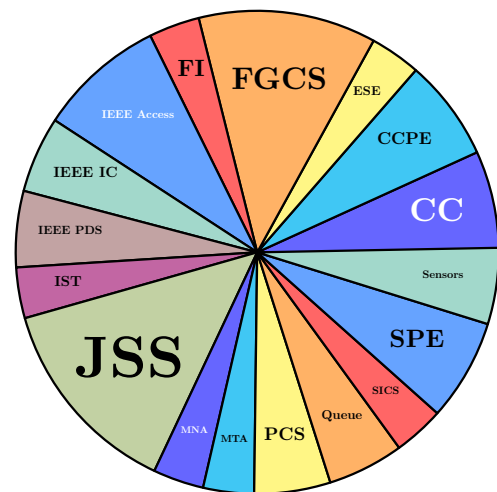
Figure 4. Journals with the largest number of publications in our dataset.

Insights

Fragmentation of outlets: there are no reference venues for the area of microservice security (neither journals nor conferences). This makes it difficult for researchers and practitioners to keep up with the state of the art, as well as to find dedicated conventions where they can discuss this topic with the rest of the community interested in the area.

426

5.1.2 Research Communities

To add more insight on the communities of the field, we also perform a network analysis to identify and explore the clusters of the most prolific authors and their research collaborations. Specifically, we are interested in analysing the networks of collaboration of "core authors", i.e., prolific authors that, by working with different people, act as a liaison among separated groups of authors.

To find the clusters of core authors in our dataset, we consider all the authors in the dataset and we aggregate them in clusters such that each member of a cluster has at least one contribution published with one of the members of the cluster. Since we are interested in "core authors"—i.e., authors with more than 2 works in the dataset—we remove all those clusters formed around just one work—i.e., where the maximum number of publications published by the most prolific author is one.

Cluster	Author	# pub.	Affiliation	Cluster	Author	# pub.	Affiliation
A	Fetzer Christof	3	TU Dresden	G	Makitalo Niko	1	University of Helsinki
A	Brito Andrey	2	Universidadede Campina Grande	H	Jin Yike	1	Unknown affiliation
A	Kopsell Stefan	2	TU Dresden	H	Yu Dongjin	1	Hangzhou Dianzi University
A	Pietzuch Peter	2	Imperial College London	H	Zhang Yuqun	1	Southern University
A	Pasin Marcelo	2	University de Neuchâtel	H	Zheng Xi	3	Xi'an Jiaotong University
A	Felber Pascal	2	University of Neuchâtel	H	Zhang Chong	2	Chong Qing Hospital
A	Fonseca Keiko	1	Universidade do Paraná	H	Liu Xiao	2	Tsinghua University
A	Rosa Marcelo	1	University of Melbourne	H	Li Rui	2	Facebook
A	Gomes Luiz	1	Arizona State University	H	Liu Huai	2	University of Washington
A	Riella Rodrigo	1	Universidade do Paraná	I	Donahoo Michael J	2	Carnegie University
A	da Silva MS Leite	1	Universidade Campina Grande	I	Cerny Tomas	6	Baylor University
A	de Oliveira SV Fernando	1	Universidade de Campina Grande	I	Sedlisky Filip	1	University In Prague
A	Kelbert Florian	1	Elastic	I	Walker Andrew	2	Carnegie University
A	Gregor Franz	1	TU Dresden	I	Svacina Jan	2	Baylor University
A	Pires Rafael	1	University of Sao Paulo	I	Bushong Vincent	2	Baylor University
A	Schiavoni Valerio	1	University of Neuchâtel	I	Bures Miroslav	2	University In Prague
A	Mazzeo Giovanni	2	MDM-IMM-CNR lab	I	Tisnovsky Pavel	2	University In Prague
A	Oliver John	1	UC Berkeley	I	Frajtak Karel	2	University in Prague
A	Romano Luigi	1	Università della Campania	I	Shin Dongwan	2	Korea Institute of Energy Research
A	Brenner Stefan	1	TU Braunschweig	I	Huang Jun	2	Duke University
A	Hundt Tobias	1	UCL Institute of Child Health	J	Yarygina Tetiana	4	University of Bergen
A	Kapitza Rudiger	1	TU Braunschweig	J	Otterstad Christian	3	University of Oslo
B	Artac	1	Necmettin Erbakan University	J	Lysne Olav	1	Simula Research Laboratory
B	Casale Giuliano	2	Imperial College London	J	Hole Kjell J	1	Simula Research Laboratory
B	Van Den Heuvel W-J	2	Tilburg University	J	Ytrehus	1	University of Tromso
B	van Hoorn Andre	5	University of Stuttgart	J	Aarseth Raymond	1	University of Tromso
B	Jakovits Pelle	1	University of Tartu	J	Tellnes Jorgen	1	University of Bergen
B	Leymann Frank	1	University of Stuttgart	J	Bagge Anya Helene	1	University of Bergen
B	Long Madeleine	1	University of Oslo	K	Cecconi Alessio	1	Vienna University
B	Papanikolaou Vicky	1	National School of Public Health	K	Di Ciccio Claudio	1	Sapienza University of Rome
B	Presenza Domenico	1	University of Rome	K	Dumas Marlon	1	University of Tartu
B	Russo Alessandra	1	University of Catania	K	Garcia-Banuelos Luciano	1	Tecnologico de Monterrey
B	Chesta Cristina	1	University of Chester	K	Lopez-Pintado Orlenys	1	University of Tartu
B	Di Nitto Elisabetta	1	Politecnico di Milano	K	Lu Qinghua	3	universtiy of delaware
B	Gouvas Panagiotis	2	University of Athens	K	Mendling Jan	1	Humboldt-Universität zu Berlin
B	Stankovski Vlado	2	University of Ljubljana	K	Tran An Binh	1	CSIRO
B	Symeonidis Andreas	1	University of Thessaloniki	K	Weber Ingo	3	TU Berlin
B	Zafeiropoulos Anastasios	2	University of Athens	K	Binh Tran An	2	CSIRO
B	Soldani Jacopo	1	University of Pisa	K	O'Connor Hugo	2	CSIRO
B	Avritzer Alberto	4	eSulabSolutions	K	Rimba Paul	2	CSIRO
B	Ferme Vincenzo	3	Kiratech S.p.A.	K	Xu Xiwei	2	National Institute of Natural Hazards
B	Janes Andrea	3	The James Hutton Institute	K	Staples Mark	2	CSIRO
B	Russo Barbara	3	Free University of Bozen-Bolzano	K	Zhu Liming	3	CSIRO
B	Schulz Henning	3	Novatec Consulting GmbH	K	Jeffery Ross	2	Mayo Clinic
B	Menasche	3	University of Rio de Janeiro	L	Mirri Silvia	2	University of Bologna
B	Rufino Vilc	3	UFRJ	L	Melis Andrea	4	University of Bologna
B	Trubiani Catia	1	Gran Sasso Science Institute	L	Prandi Catia	2	University of Bologna
B	Bran Alexander	1	University of Exeter	L	Prandini Marco	4	University of Bologna
C	Rocha Carla	1	Rutgers University	L	Salomoni Paola	2	University of Bologna
C	Leite Leonardo	3	University of São Paulo	L	Callegati Franco	3	University of Bologna
C	Kon Fabio	3	University of São Paulo	L	Giallorenzo Saverio	2	University of Bologna
C	Milojicic Dejan	1	Hewlett Packard Labs	L	Delnevo Giovanni	1	University of Bologna
C	Meirelles Paulo	3	University of São Paulo	L	Monti Lorenzo	1	University of Bologna
C	Pinto Gustavo	2	University of São Paulo	M	Panichella Annibale	4	Delft University of Technology
D	Hou Kaiyu	3	Northwestern University	M	Jan Sadeeq	1	Technology Peshawar Pakistan
D	Wu Xiaochun	3	Zhejiang University	M	Arcuri Andrea	1	Kristiania University College
D	Leng Xue	3	Zhejiang University	M	Briand Lionel	1	University of Ottawa
D	Li Xing	3	University of Chicago	M	Olsthoorn Mitchell	2	Delft University of Technology
D	Yu YinBo	1	Wuhan University	M	van Deursen Arie	2	Delft University of Technology
D	Wu Bo	3	Google Inc.	N	Zimmermann Olaf	5	HSR University of Rapperswil
D	Chen Yan	3	Lunghwa University	N	Stocker Mirko	1	HSR University of Rapperswil
D	Yu Yinbo	2	Wuhan University	N	Zdun Uwe	3	University of Vienna
E	Nikouei Seyed Yahya	3	Binghamton University	N	Lubke Daniel	1	Leibniz Universität Hannover
E	Xu Ronghua	2	Binghamton University	N	Pautasso Cesare	1	University of Lugano
E	Chen Yu	3	University of Singapore	N	Kapferer Stefan	2	Witten/Herdecke University
E	Blasch Erik	2	Air Force Research Lab	N	Wittern Erik	2	Witten/Herdecke University
E	Aved Alexander	2	US Air Force Research Lab	N	Leitner Philipp	2	University of Gothenburg
E	Nagothu Deeraj	1	Binghamton University	O	Michalas Antonis	1	Tampere University of Technology
E	Faughnan Timothy R	1	Binghamton University	O	Paladi Nicolae	1	Research Institutes of Sweden
F	Sukaridhoto Sritrusta	3	Politeknik Surabaya	O	Dang Hai-Van	3	University of Westminster
F	Panduman YY Fridelin	1	Politeknik Surabaya	O	DesLauriers James	2	CNRS
F	Tjahjono Anang	1	Politeknik Surabaya	O	Kiss Tamas	2	CNRS
F	Falah Muhammad Fajrul	2	Politeknik Surabaya	O	Ariyattu Resmi C	2	Carleton University
F	Al Rasyid MU Harun	2	Politeknik Surabaya	O	Ullah Amjad	2	Carleton University
F	Wicaksono Hendro	2	Politeknik Surabaya	O	Bowden James	2	Carleton University
G	Kilamo Terhi	1	Aalto University	O	Krefting Dagmar	2	HTW Berlin
G	Lwakatare Lucy Ellen	1	University of Helsinki	O	Pierantoni Gabriele	2	University of Westminster
G	Karvonen Teemu	1	University of Helsinki	O	Terstyanszky Gabor	2	University of Westminster
G	Heikkila	1	University of Oulu	P	Basso Tania	1	Universidade Estadual de Campinas
G	Itkonen Juha	1	Aalto University	P	Antunes Nuno	3	University of Coimbra
G	Kuvaja Pasi	1	Aalto University	P	Vieira Marco	1	University of Coimbra
G	Mikkonen Tommi	2	University of Helsinki	P	Santos Walter	1	Universidade Estadual de Montes Claros
G	Oivo Markku	1	University of Oulu	P	Meira Wagner	1	Universidade Federal de Minas Gerais
G	Lassenius Casper	1	Aalto University	P	Flora Jose	4	University of South Carolina
G	Kalske Miika	1	University of Helsinki	P	Goncalves Paulo	2	Universidade de São Paulo

Table 2. Cluster Authors Correspondence.

Our analysis extracted 16 clusters from our dataset. We report in Table 2 the result of our analysis, labelling each cluster from **A** to **P**. For each Cluster, we report the name of the author, the number of publications (# pub.) in our dataset and their affiliation.

The measure gives some interesting insights. First, clusters **F**, **G**, **J**, and **L** are totally localised in one country or the same University/Institute, they are relatively small (compared to the others in the Table), and include some of the most prolific authors (**J** and **L** in particular). Four other clusters follow a different trend: **C**,**H**,**P** and **I**. They are big-size clusters (respectively 6,10,8 and 6), they count one core author (respectively with 3,3,4 and 3 publications) but they are rather homogeneous, the first mainly including authors from Brazil, Finland and the fourth one is from Portugal. Clusters **A**, **B**, **D**, **K**, **M**, **N** and **O** are the most varied. Cluster **A**, is the largest (22 authors) and most heterogeneous one: it includes 6 core authors from 5 different countries (Brazil, Germany, Italy, Switzerland, and the UK) and 12 co-authors from 4 countries different from those of the core authors (Australia, France, Portugal and the US). Cluster **B** includes 6 core authors over 24 members, distributed over just 5 countries (Brazil, Germany, Italy, Greece and Switzerland). Cluster **D** includes 8 authors, of which 6 are core and come both from either China or the US. Cluster **K** is another big cluster of 16 authors with include 3 core authors from the US and Germany. Clusters **M**, **N** and **O** follow the same trend of cluster **D**. This means that these clusters are built around 2 core authors which represent the main affiliation provenance, respectively Holland, Germany and Switzerland, US and UK.

Overall, the communities of core authors in the dataset is distributed among three types of clusters:

- "open" clusters (**A**, **B**, **D**, **K**) of co-authors linked by a few (if not one) core authors and diverse affiliations;

- "semi-open" clusters (**C**, **G**, **M**, **N** and **O**) of localised collaborators with sporadic, external collaborations;

- "closed", localised clusters (**F**, **L**, , **P**) that tend to be small but whose core authors tend to be the most prolific (**L**).

Given their larger reach, semi-open and open clusters have a better chance to gather an impactful community around the topic. Our call to the authors in the field (particularly the closed clusters that tend to be prolific but rather localised) is to establish international collaborations and coordinate to foster the advancement and growth of the field.

5.1.3 Concepts and Keywords

We conclude our quantitative analysis by providing a graphical representation of the main keywords present in the abstract of the contributions in our dataset. To conduct our analysis, we used VOSviewer by Van Eck and Waltman (2010), a software that offers text mining functionalities for constructing and visualising co-occurrence networks of important terms extracted from a given corpus. Specifically, we ignored basic words and copyright statements and performed a full count of the words present in the text. We considered only words occurring more than fifteen times, sizing them by their relevance in terms of occurrences. The resulting graph, however, is still too large and dispersive to convey useful information: for the sake of clarity, we present here a visualisation including only the top 60% most-occurring words.

We report the visualisation of the analysis in Fig. 5.

VOSviewer automatically clustered the words in 4 areas using its modularity-based clustering algorithm, which is a variant of the cluster algorithm developed by Clauset et al. (2004) to detect communities (clusters) in a network that also considers modularity.

We can interpret the clusters as follows:

- The blue area marks the main terms of this study, grouping words like *microservice* and *system*. The result does not surprise, since those words describe the design of the systematic selection we performed.

- The green area marks technical terms as *container* or *attack*.
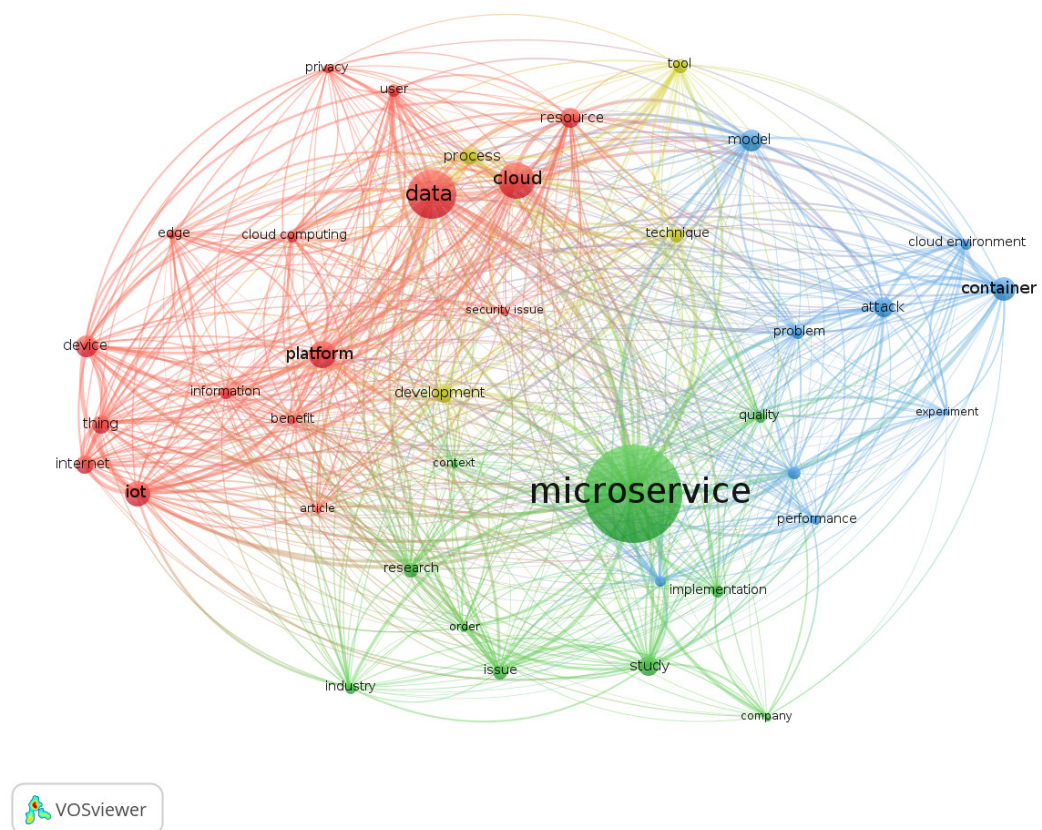
Figure 5. Word-Net of the abstracts in our dataset.

- The red area identifies application terms, e.g., the targets or reasons of the research, if it is an industrial or research-focused article. We find for instance the word *Internet-of-Things*, as it is mainly cited with industry and research applications rather than along with terms like *container* and *cloud*.

- The yellow area includes words that identify the subject of a study, whether it be some *tool*, *data* (of the system, of the users), *user*s, and they *privacy*. The word *tool* here is peculiar, as it acts as a bridge between the other areas. Also, this finding is somehow expected, as the field of microservice security is marked by a fairly practical orientation towards automatisation of processes and control.

5.2 Publication Context Analysis
In this section, we discuss trends and considerations derived from reading the selected publications and the research question detailed in Section 4.

5.2.1 Types of Publications
In Fig. 6 we report the distribution of the type of research contribution—whether theoretical, practical, mixed or a review.

More precisely, regarding the type of research contribution, we mapped every publication in our dataset to one of the following types:

- *Theoretical* for publications that present an approach for a specific problem without any implementation artefact.
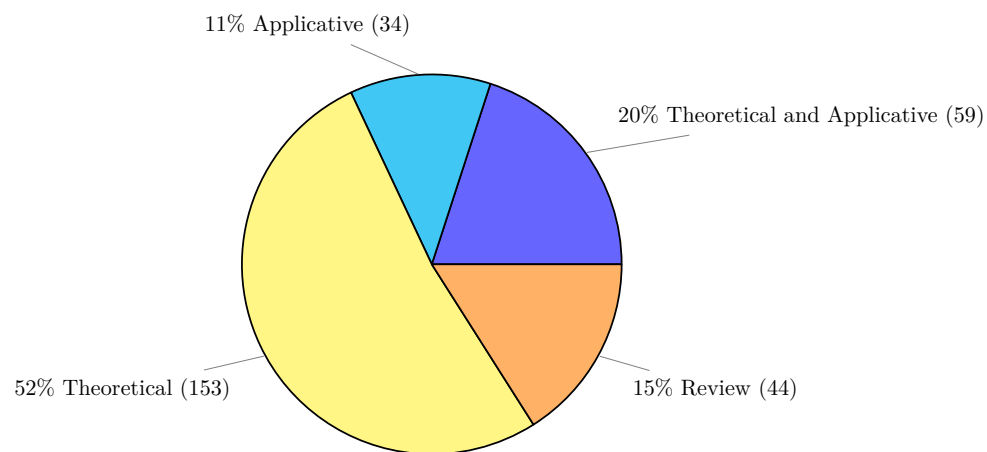
Figure 6. Type of publications.

508   • *Applicative* for publications that describe an implemented application possibly with its
509   validation.

510   • *Theoretical and Applicative* for publications that develop a theory and provide a practical
511   tool, framework, program, or application.

512   • *Review* for both literature reviews and social studies (e.g., on developers).

513 Reviews constitute 15% of the works, marking the fragmented shape of the field, which is in
514 rapid expansion and in need of studies to map its research landscape. Besides reviews, the other
515 contributions in the field are distributed among a 52% share that introduces new theoretical
516 results, a 20% share that contributes by pairing new theoretical proposals with implementations,
517 and the remaining 11% describing pure applications. The fact that the main publications in the
518 field are theoretical is surprising, given the prominently applied nature of microservices. Indeed,
519 excluding reviews, we have that for every 5 publications slightly more than 3 (64% of them)
520 are purely theoretical. We attribute this figure to two phenomena. The first marks the current
521 exploratory trend of the field, which is still engaged in proposing new ideas and in evaluating
522 and maturing them into models amenable to implementation. The second phenomenon relates
523 to the impact that microservices have at the processes/organisational level, with works that are
524 intrinsically theoretical because their contribution can be hardly crystallised into automated
525 implementations, e.g., for proposals of attack models or techniques for handling security within
526 organisations and development teams. Notwithstanding the possible explanations above, it is
527 worth noting the (quantitative) distance between contributions from academia and applications
528 available to practitioners and the industry, which is an indicator of untapped potential for joint
529 synergies between the two communities.
530   After having characterised the type of publications in the field, we proceed by exploring the
531 results from the answer of the research questions following the 4 macro-groups presented in
532 Section 4.

> **Insights**
>
> **Technology transfer**: the field of microservice security is still in the early phase of
> new idea proposals. There are just a few implementations of these ideas, which hinders
> industrial adoption.

533

5.2.2 Threat Model

535 176 publications (ca. 65% of the dataset) give a positive answer to at least one question of
536 this category. However, only 53 publications among those 120 (ca. 30% of the total dataset)
537 mentioned the usage of at least one threat model to analyse or classify threats The reason for
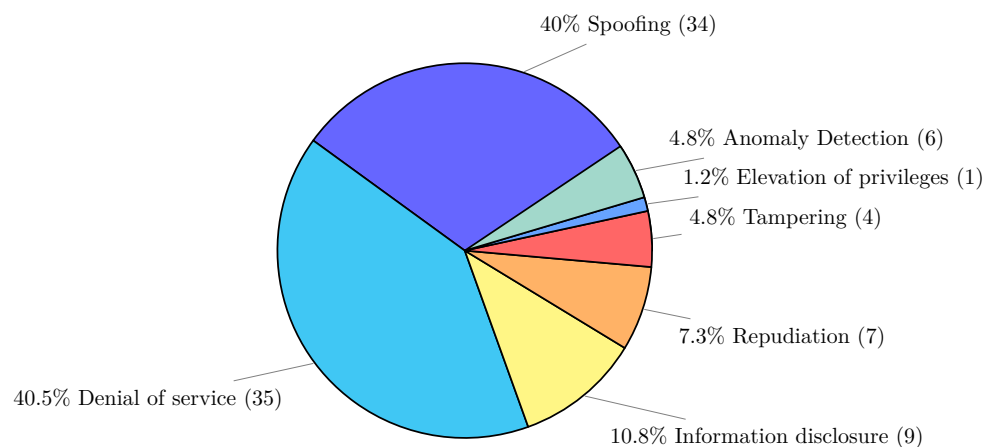
Figure 7. Attack type identified following the STRIDE classification.

those publications to adopt a threat model vary, from publications that use the model to motivate their proposed solutions to reviews that use the model to structure their overview of the state of the art. Interestingly, in ca. 80% of those publications that mention the usage of at least one known threat model, the model is tailored to work on a specific application scenario. This is an indication of the lack of usage of a generic threat model for microservice security. We conjecture that this lack of usage of generic threat models is due to the fact that the majority of research done on microservice security comes from the software (engineering, languages) side of the field, rather than from the side of security, which advocates for a security-by-design approach.

A complementary explanation of that phenomenon is that there is no affirmed threat model for microservices, e.g., due to the difficulty of making the model specific enough for microservices yet avoiding the infamous problem of threat explosion, where the effort required to prioritise and consider all threats starts exceeding the benefits of proposing methods to manage them Wuyts et al. (2018). Threat explosion is a known problem of neighbouring areas to microservices, like cloud, edge, and fog computing Di Francesco et al. (2017); Ibrahim et al. (2019); Guija and Siddiqui (2018); Lou et al. (2020); Flora (2020); Truong and Klein (2020); Russinovich et al. (2021) where the authors resorted to defining smaller, customised threat models rather than adopting standard ones, due to the problem of requiring conspicuous adaptation efforts to tailor them to such complex and multifaceted architectures.

Regarding the possible attacks addressed in the publications, Fig. 7 categorises the publications based on the STRIDE threats, following up on question Q2 asking if the publication involves at least one of threats of the STRIDE classification. The most commonly tackled attacks are of the "spoofing" and "denial of service" kinds. This is an effect of the push for fine-granularity and independence of services advocated by microservices, where applications result from several small (in size), independent software components that communicate with each other. Such decentralised communication/coordination is one of the most important attack vectors for microservice applications, in particular, the possibility to disguise a communication from an unknown source as being from a known, trusted source, which matches the spoofing attack category. Such attacks, along with tampering and repudiation ones (which together represent more then half of the attack types found in our collection), entail the need for solutions to address attacks centred around exploits of data provenance.

A similar consideration can be made for denial-of-service attacks, where the flexible scalability of microservices allows malicious intruders to, e.g., scale up peripheral microservices and hit more central and well-protected components with (distributed) overpowering attacks.

> **Insights**
>
> **Adoption of security-by-design**: security in microservice frequently comes as an afterthought, whereas it should be one of the main concerns for their engineering.
> **Data provenance**: the quantity of spoofing, tampering, and repudiation attacks highlights the need to address the general problem of data provenance in microservices.
> **Dedicated attack trees and threat models**: while there are attacks that specifically pertain to microservices, such as those that leverage the scalability of microservice architectures to cause denial of service, there are no dedicated threat models to help developers become aware of those particular threats.

5.2.3 Security Approach (Mitigation)

In terms of mitigation solutions to security issues proposed by the publications (questions Q6–Q10), the most common approach (45 publications) is to address specific problems, such as authentication or exfiltration, rather than suggesting a general approach. Publications dealing with architectural aspects rarely address the overall picture (only 25, roughly 8%, publications focus on IDS, IPS, Exfiltration Leaks and Threat Intelligence). Again, they focus on local threats like intra-communications or authentication (question Q11). These observations suggest that there is a lack of security approaches that address applications across the full stack.

As far as privacy and GDPR are involved (question Q12), surprisingly, only 9 publications consider privacy protection as relevant or worthy of analysis. In particular, only one publication Badii et al. (2019) considers the GDPR as a guideline to follow in order to protect the privacy of users. Examples of this kind of guideline application are shown in Voigt and Von dem Bussche (2017). Considering that many of the solutions included in the dataset are Cloud-based solutions, it is surprising to note that only one publication claims to be GDPR compliant.

> **Insights**
>
> **Global view/control**: the distributed nature of microservices introduces the need for technologies that provide global yet decentralised observability and control, i.e., tools that aid in the enforcement of security policies over a whole architecture without single points of failure.
> **React & recover techniques**: while we found solution to prevent and detect attacks, there are only a few proposals about how microservice systems could react to and recover from them.
> **Comprehensive technological references**: microservices use diverse sets of technology stacks, each characterised by peculiar exploits. To secure microservice architectures effectively, implementors need dedicated technological references to avoid known threats.

5.2.4 Infrastructure

We start the discussion by first focusing on the type of microservice infrastructure used by the various contributions. Specifically, we have 205 publications in our dataset that answer positively to question **Q13**. The breakdown of the answers is:

- 39% (80) describe a centralised approach;

- 24% (49) use a decentralised approach;

- 17% (35) resort to a hybrid approach;

- 20% (41) do not specify which approach they use.

The most widely adopted turns out to be the centralised one. We conjecture two explanations behind this observation. First, the centralised approach has the merit of simplifying the definition, deployment, monitoring, and evolution of policies holding over all the components in a given architecture—traded off with scalability issues and single-point-of-failure concerns. Second,

we note that, among the approaches that appeared early in the literature, many focused on converting monolithic applications into microservice applications. Clearly, having a centralised controller that manages the orchestration of microservices helps this process and is closer in spirit to the monolithic workflow. However, the advent of federated, multi-cloud solutions (that prevent the identification/deployment of a centralised authority over the whole peer network) as well as new distributed-consensus technologies (e.g., blockchains), has led to a decentralisation of control, making new decentralised or hybrid solutions emerge (in our dataset) starting from 2018. As an example, in 2015 and 2016, we find publications such as Callegati et al. (2016) and Lysne et al. (2016) which presented centralised approaches to enable security in microservice platforms, while starting from 2018 hybrid and decentralised solutions appear like Pahl and Donini (2018) for certificate-based authentication or Andersen et al. (2018), Andersen et al. (2017) where authors propose a decentralise high-fidelity city-scale emulation to verify the scalability of the authorisation tier.

We notice that the advent of new distributed-consensus technologies also affected the orchestration approach of microservice solutions. For example, works such as Xu et al. (2019b) propose a decentralised, blockchain-based data-access control for microservices. Recent contributions also tackled the problem of authentication and authorisation in decentralised settings, e.g., Bánáti et al. (2018) develops a workflow-oriented authorisation framework to enforce authorisation policies in a decentralised manner, Taha et al. (2019) presents a new algorithm that distribute tasks on clusters of vehicular ad-hoc networks, Zhiyi et al. (2018) proposes a secure decentralised energy management framework, and Tourani et al. (2019) describes a decentralised data-centric SECurity-as-a-Service (SECaaS) framework for elastic deployment and provisioning of security services. Another interesting work has been done in Falah et al. (2020) where authors brought the concept of a digital twin to show how a microservice infrastructure approach can speed up the process of deploy complex infrastructure components.

Infrastructure as a Service (IaaS), which is the focus of question Q14, is also a recurrent topic in our dataset, with 66 publications yielding a positive answer. IaaS include solutions that provide and manage low-level infrastructural components, like computing resources, data storage, network components, etc. We notice that IaaS is mentioned mainly as the modality used to deploy the solution but is not studied as a security subject/mechanism per se. Works such as Sultan et al. (2019) emerge as exceptions; their authors analysed the security benefits obtained using a container-based infrastructure exposed as a service.

Question Q15 investigates Service Discovery, i.e., the automatic detection of services and their functionalities available in a given architecture/network. 16 publications mention Service Discovery in the context of security. Mainly, they propose architectures that support reactive mechanisms for the detection of security issues. Of those, only 2 mention service registration procedures that include data for performing the preventive analysis of the composition, with the goal of statically finding and fixing possible vulnerabilities and misconfigurations: Callegati et al. (2018) and Kamble and Sinha (2016).

> **Insights**
>
> **Global view/control**: while there is not a definitive approach to microservice security control (whether it be centralised, decentralised, or hybrid), there is a recognised need for applying security control policies in a consistent way across all microservices belonging in the same architecture.

5.2.5 Development

DevOps and Agile are recurring topics in our dataset. Based on the answer to question Q16, 76 publications used the DevOps approach, while, answering to Q17, 57 used Agile methods—of those 99 publications which represent the 40% of all publications in our dataset, 10 mention both approaches. There is a common consensus in these publications that Agile/DevOps is important in security because microservices seem to be the perfect match for this type of software development model (Vehent (2018); Hsu (2018)). In particular, microservices align with the tenet of both approaches: to assign dedicated, independent teams to the development of small and

independent components within the architecture Continuous Integration (CI) process. However, the majority of the selected publications provide no in-depth security analysis of any of the two development approaches, but rather indicate the inclusion of generic security measures in the steps of the development methods. Only three works, namely Mansfield-Devine (2018), Anisetti et al. (2019) and Kumar and Goyal (2020), propose concrete and specific variants of the DevOps approach that tackle security issues—in particular Mansfield-Devine (2018) explicitly cites the guidelines of DevSecOps Hsu (2018).

Migration is one of the main challenges faced in this context; migrating applications introduces important security concerns Lwakatare et al. (2019) that are difficult to track, due to the lack of appropriate devices (both organisational and linguistic) to elicit them from the source codebase and make sure they hold in the migrated one. Another major challenge is the coordination between development teams in the context of privacy-handling issues Gupta et al. (2019). Also, security becomes a challenging aspect since the (small, independent) teams need to know many aspects of security Leite et al. (2019) and those DevOps criteria for testing, building, and deployment automation are often neither properly followed in industrial environments Bogner et al. (2019), nor for automated scans Chondamrongkul et al. (2020).

When considering domain- and model-driven approaches (questions Q18 and Q19), 16 publications consider domain-driven approaches and 26 consider model-driven ones, such as Kapferer and Zimmermann (2020); Avritzer et al. (2020). These topics are therefore not as widespread as DevOps. Moreover, all citations in these cases are just brief references of the development approach, and lack a discussion on how one of the two approaches can be used in a security context on microservices.

The last question in this category, Q20, concerns security standards, i.e., curated sets of technologies, policies, concepts, safeguards, guidelines, assessments, procedures, training programmes that should be adopted to reduce security risks and mitigate attacks. The answers we gathered for this question surprised us. Indeed, security standards are a staple element of industries and organisations that want to impose and guarantee a certain level of security on their members and collaborators (often also for certification purposes – Stewart et al. (2012), Lie et al. (2020)). Despite their widespread use in practice, only 7 publications mention security standards. In particular, Souppaya et al. (2017) mentions the usage of X.509 to verify a secure method for key exchange between microservice. In Brenner et al. (2017) the authors show a solution for securing microservices through the SGX Intel Standard. The authors of Vassilakis et al. (2016) analyse the concept of Small-Cell-as-a-Service, i.e., a technological paradigm for the development of Virtualised Mobile Edge Computing Environments, using several mobile standards for 5G and SDN networks (e.g., MobileFlow Pentikousis et al. (2013) and VNFs Agarwal et al. (2019)). Finally, Yarygina (2018) performs a deep analysis on securing microservices, citing and analysing several know standards for both microservice management and security purposes.

> **Insights**
>
> **Migration to microservices**: there are no established techniques to help developers migrate legacy systems to microservice architectures, and in particular to identify the possible security threats that come from such a migration.
>
> **DevSecOps**: agile and DevOps practices are widely used when developing microservices, yet only a few publications address how security is addressed and combined in these practices.

5.2.6 Additional considerations

By analysing our dataset, we were surprised to find many citations to blockchain technologies (as reported above) as well as the lack of mainstream technologies like service mesh and serverless.

Regarding blockchain technologies, we found 31 publications mentioning or explicitly using blockchains. The decentralisation and independence of microservices constitute a good pairing for the usage of blockchain technologies. Fig. 8 presents also the trend of publications using blockchain in the dataset. There is an increasing interest in blockchain applications for microservice architecture. Examples of that pairing include works such as Nagothu et al. (2018); Xu et al.
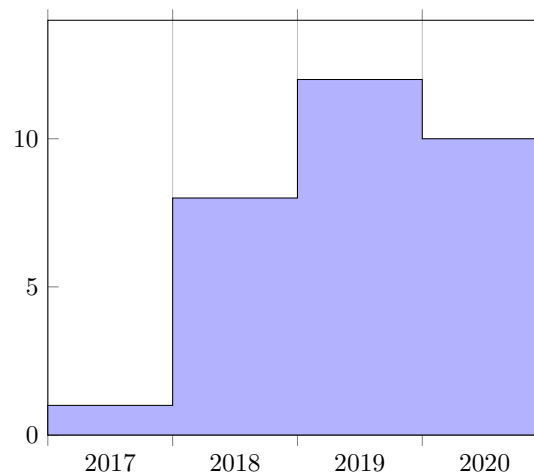
Figure 8. Blockchain trend.

(2019b), where the trust-chain of the blockchain is combined with a decentralised microservice architecture to create strong smart contract systems or Lu et al. (2021) where authors proposed a model-driven engineering approach for blockchain applications with microservice.

New approaches for microservices design and usage such as service mesh Li et al. (2019), i.e., a dedicated infrastructure layer for facilitating service-to-service communications between microservices is just mentioned by 3 works: Pahl and Donini (2018), where the authors indicate a service mesh architecture for authenticating services—securely adding information to their executables and validating the correct execution of distributed entities with such certificate-based approach—and Suneja et al. (2019), which mentions the service-mesh sidecar pattern used to control security. Another interesting work regarding service mesh is Hahn et al. (2020) where authors analysed under several scenarios issues and challenges in Service Meshes

Similarly, serverless Hendrickson et al. (2016) is mentioned only in 4 publications. We did not expect to find (50%) more citations of serverless than those regarding service mesh. Serverless is a cloud computing execution model in which the cloud provider dynamically manages the allocation/scaling of machine resources depending on inbound requests. Indeed, while the service mesh is a technology born within the (micro)service-oriented context, serverless is a more neighbouring concept to that of stateless microservice deployment.

In this context, the most relevant publication is Casale et al. (2019), which presents the results of a European research project to develop a model-driven DevOps framework for creating and managing applications based on serverless computing. Its main result consists in designing applications as fine-grained and independent microservices that can efficiently and optimally exploit the serverless paradigm. The serverless term, despite starting to get momentum, is still loosely related to microservices.

Given their increasing importance and impact in the industry and their close relation with microservices, we argue that both service mesh and serverless will attract the general attention of the research community in the near future, as well as that of security research.

> **Insights**
>
> **Comprehensive technological references**: the progressive adoption of new technologies in the world of microservices (such as blockchains, service meshes, and serverless) calls for dedicated investigations and reports on their impact on the security of these systems.

5.2.7 Correlation between Research Questions

The amount of data collected in our dataset is large enough to represent a statistically-relevant sample. In this section, we leverage this to study correlations between our research questions, by

	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Q9	Q10	Q11	Q12	Q13	Q14	Q15	Q16	Q17	Q18	Q19	Q20
Q2		27.11%	32.80%	8.10%	13.75%	3.19%	-7.74%	12.36%	0.41%	24.68%	-4.12%	-22.74%	-8.06%	6.27%	-3.88%	-6.71%	8.45%	0.19%	0.41%
Q3	27.11%		28.59%	7.37%	18.93%	29.11%	7.49%	8.68%	12.81%	16.69%	8.54%	0.75%	5.51%	15.10%	-6.93%	-10.82%	3.57%	2.26%	12.81%
Q4	32.80%	28.59%		12.18%	6.30%	5.05%	10.50%	6.05%	8.45%	17.28%	9.01%	-10.39%	-7.34%	-0.42%	1.05%	1.34%	6.88%	-6.90%	8.45%
Q5	8.10%	7.37%	12.18%		6.15%	8.26%	12.31%	5.58%	13.51%	-12.44%	5.04%	-2.41%	5.31%	9.24%	-10.48%	-7.12%	-13.61%	-9.07%	8.06%
Q6	13.75%	18.93%	6.30%	6.15%		77.49%	22.89%	14.23%	14.86%	3.83%	5.58%	0.88%	17.76%	14.23%	-0.42%	2.99%	6.90%	4.96%	-5.83%
Q7	3.19%	29.11%	5.05%	8.26%	77.49%		20.77%	12.55%	17.68%	1.97%	0.88%	0.78%	15.67%	12.55%	4.41%	-1.48%	10.17%	7.44%	-5.14%
Q8	-7.74%	7.49%	10.50%	12.31%	22.89%	20.77%		10.03%	14.15%	-5.27%	20.31%	20.12%	31.15%	13.76%	8.28%	9.01%	4.83%	-4.89%	-8.03%
Q9	12.36%	8.68%	6.05%	5.58%	14.23%	12.55%	10.03%		25.72%	3.19%	13.09%	-0.84%	15.70%	14.01%	-0.66%	3.25%	8.28%	14.01%	-3.80%
Q10	0.41%	12.81%	8.45%	13.51%	14.86%	17.68%	14.15%	25.72%		8.88%	10.14%	0.37%	7.54%	6.04%	5.95%	3.53%	2.93%	6.04%	12.17%
Q11	24.68%	16.69%	17.28%	-12.44%	3.83%	1.97%	-5.27%	3.19%	8.88%		0.36%	5.13%	-17.71%	0.15%	12.62%	9.16%	9.02%	6.24%	8.88%
Q12	-4.12%	8.54%	9.01%	5.04%	5.58%	0.88%	20.31%	13.09%	10.14%	0.36%		-1.44%	9.26%	4.38%	-1.62%	6.16%	1.34%	-4.32%	-2.81%
Q13	-22.74%	0.75%	-10.39%	-2.41%	0.88%	0.78%	20.12%	-0.84%	0.37%	5.13%	-1.44%		26.24%	9.08%	11.22%	13.12%	7.16%	5.77%	5.29%
Q14	-8.06%	5.51%	-7.34%	5.31%	17.76%	15.67%	31.15%	15.70%	7.54%	-17.71%	9.26%	26.24%		22.90%	10.67%	12.47%	11.75%	8.50%	-3.18%
Q15	6.27%	15.10%	-0.42%	9.24%	14.23%	12.55%	13.76%	14.01%	6.04%	0.15%	4.38%	9.08%	22.90%		13.07%	10.85%	18.85%	14.01%	-3.80%
Q16	-3.88%	-6.93%	1.05%	-10.48%	-0.42%	4.41%	8.28%	-0.66%	5.95%	12.62%	-1.62%	11.22%	10.67%	13.07%		57.34%	25.21%	19.94%	0.85%
Q17	-6.71%	-10.82%	1.34%	-7.12%	2.99%	-1.48%	9.01%	3.25%	3.53%	9.16%	6.16%	13.12%	12.47%	10.85%	57.34%		33.08%	10.85%	-2.13%
Q18	8.45%	3.57%	6.88%	-13.61%	6.90%	10.17%	4.83%	8.28%	2.93%	9.02%	1.34%	7.16%	11.75%	18.85%	25.21%	33.08%		40.00%	-4.94%
Q19	0.19%	2.26%	-6.90%	-9.07%	4.96%	7.44%	-4.89%	14.01%	6.04%	6.24%	-4.32%	5.77%	8.50%	14.01%	19.94%	10.85%	40.00%		-3.80%
Q20	0.41%	12.81%	8.45%	8.06%	-5.83%	-5.14%	-8.03%	-3.80%	12.17%	8.88%	-2.81%	5.29%	-3.18%	-3.80%	0.85%	-2.13%	-4.94%	-3.80%	

Table 3. Correlation matrix among research questions.

way of the answers that the publications in our dataset give to each of them. Correlations can be used to understand which of the different aspects of microservice security are most commonly in a positive correlation (paired) in the dataset, and which ones are negatively correlated (mutually exclusive).

We report in Table 3 the correlation matrix—excluding research question Q1, since no publication answered it. While the obtained matrix is symmetric and we could report just one half, in Table 3 we report the full matrix for convenience, to provide a more immediate view of how each question correlates with all of the other ones.

We conditionally colour the cells of the Table, first, attributing colour intensity according to correlation absolute value—maximal intensity for 100% and degrading towards 0%—, second, setting a transition threshold above 30% (absolute value) from green to orange, to help to spot relevant correlations. Looking at the Table, we notice the predominance of light-coloured cells. This result can be interpreted as an indication that the research questions used in this work are mostly orthogonal, and thus suited to cover the reviewed subject with almost no wasteful overlap.

No anti-correlation was found, i.e., negative correlations over the 30% threshold in absolute value. In the following, we comment on all positive correlations above 30%.

Q2–Q4 (32,80%) The questions relate the use of STRIDE threat model with one of is identified specific threats. This seems to be an obvious correlation since we are looking for a specific STRIDE path or at least one of his threats.

Q7–Q6 (77,49%). The questions ask if the publication mentions IPS or IDS functionalities respectively. The strong correlation indicates how IPS and IDS are strictly related. Indeed, in practice, IDS may exist without IPS, but not the opposite, because prevention mechanisms are typically built as a reaction to a detected attack;

Q8–Q14 (31,15%) The questions relate Threat Intelligence functionalities with Infrastructure as a Service deployment, which can define a campaign strategy for a Threat Intelligence analysis.

Q17–Q16 (57,34%) The questions relate the Agile development practice with DevOps and Continuous Integration. As also emphasised in other studies like Lwakatare et al. (2019), this correlation can be easily explained by the fact that DevOps is sometimes considered an Agile method or its evolution. Processes adopting DevOps, therefore, adopt also Agile;

Q19–Q18 (40,00%) The questions relate Domain-Driven Development and Model-Driven Development. We conjecture that this correlation is present because mentions of Domain-

756   Driven Development often mentions Model-Driven Development as an alternative approach
757   and vice versa;

758   **Q18–Q17 (33,08%)** The questions relate Domain-Driven Development and Agile methods,
759   indicating a correlation, mainly because often Agile methods employ Domain-Driven
760   Development.

5.3 Threats to validity

762   Our study is subject to limitations that can be categorised into construct validity, external
763   validity, internal validity, and reliability following the guidelines of Runeson et al. (2012).

764   *Construct validity* "reflects to what extent the operational measures that are studied really
765   represent what the researcher has in mind and what is investigated according to the research
766   questions.". To mitigate a potential misinterpretation and making sure that the constructs
767   discussed in the interview questions are not interpreted differently by the researchers, we adopted
768   various triangulation rounds using online meetings and we designed a set of binary research
769   questions to foster objectivity in answering them.

770   Another potential risk regards whether we were exhaustive during data collection, i.e., whether
771   we may have missed any significant publication in our review. This risk cannot be completely
772   mitigated but to minimise this risk we deliberately chose to have simple and broad keywords
773   giving more initial hits that later were further filtered out. Moreover, we conducted a snowballing
774   process to extend our initial dataset looking for potentially relevant publications that our query
775   did not select.

776   *External validity* regards the applicability of a set of results in a more general context and is
777   not a concern for this study since we focus on the intersection of the fields of microservices and
778   security without any attempt of generalising the findings to a broader context. We do not claim
779   that either our qualitative or our quantitative findings should also hold for other large fields.

780   *Internal validity* is of concern when causal relations are examined when there is a risk that
781   the investigated factor is also affected by a third factor. This thread is not a concern for this
782   study because we presented only correlations between different factors but did not examine
783   causal relations.

784   *Reliability* concerns to what extent the data collection and analysis depend on the actual
785   researchers. This risk has been partially mitigated by selecting as many objective criteria
786   as possible for the filtering and by requiring at least a two-people consensus in case of more
787   subjective decisions. In particular, the retrieval of the publications was performed by using
788   search engines. The first filtering of the results (Step 2, cf. Section 3) was conducted by running
789   a script that uses objective criteria such as counting the number of keywords present and the
790   length of the publication. These automatically computed results were double-checked by at least
791   one author to prevent problems due to the parsing of PDFs and to make sure that the language
792   of the publication was English. The second filtering (Step 3, cf. Section 3) performed by reading
793   the title, abstract, and (if needed) the body of the publication, was performed in parallel by
794   two authors. Decision conflicts were solved by discussion involving at least two authors until a
795   consensus was reached. For the publication analysis (Step 4, cf. Section 3), due to the binary
796   nature and formulation of the questions, the 20 research questions were answered by the author
797   assigned to the publication. To detect possible observer bias and errors, we selected a random
798   subset of 15 papers and had a different author answer to the research questions. The calculation
799   of the kappa index of agreement as proposed in Cohen (1960) over the two result sets yielded a
800   value of $\kappa = 0.99998$, giving us statistical confidence over the perceived precision of questions
801   and objectiveness of answers.

802   The reliability of the study is strengthened by being open and explicit about the process
803   of data collection and analysis. For transparency, reproducibility, and reuse, we report the
804   data used in this study at https://doi.org/10.5281/zenodo.4774894, which includes both
805   the final dataset with the answers to all the research questions and also the set of rejected
806   publications along with the reason for exclusion.

807   We also report in the Appendix each entry of our dataset and its answers to our research
808   questions.

6 DISCUSSION AND FUTURE DIRECTIONS

In this article, we presented a systematic review of the literature regarding microservice security. To conduct our research, we followed a structured approach that allowed us to gather 290 peer-reviewed publications, which, at the time of writing, constitutes the largest curated dataset on the topic.

To study our dataset, we conducted first an investigation on the metadata of the publications, which gave us some insight to map what are the publication outlets, the communities, and the key research concepts that characterise the field. Then, we performed an analysis, associating each element in our dataset to a vector of 20 different markers—presented in the form of 20 research questions.

Since our markers belong in four micro-groups (of threat-model, security, infrastructure, and development approaches), we used that partition to provide an overview of the literature through the lenses of each cluster. As a byproduct of our analysis on the content of each publication, we found concepts and topics that we did not include in our questions but that recur in multiple publications, e.g., the usage of blockchain or service-mesh technologies. To provide a more comprehensive picture of the field, we described and contextualised also these additional elements. Since our dataset forms a statistically relevant vector field, we also performed a correlation study over the components of the vectors and reported the strongest correlations (e.g., between intrusion-detection (IDS) and intrusion-prevention (IPS) systems in microservice deployments) along with possible explanations of the identified phenomena.

In the following, we draw a summary of the main open challenges that emerged from our study, which forms a call for action for the community of researchers and practitioners working in the field of microservice security and its neighbouring areas.

Data provenance: the distributed nature of microservices calls for the certification of their outputs, which other federated services receive as input and need to trust. However, there is a lack of best practices and/or standards for such a task.

Technology transfer: there exists a sensible amount of research on microservices security, but transferring those results—e.g., viable methods and tools for validation and verification—to the industry is difficult and applications are almost non-existent.

Security-by-design adoption: while many advocate for adopting security-by-design at all stages of a microservice lifecycle (from design to monitoring), there are no established references nor guidelines on how these principles can be reliably adopted in practice.

Dedicated attack trees and threat models: threats in microservice systems can come from multiple sources, from the interaction of the layers of a chosen technology stack to how microservices interact with each other—e.g., in an exclusive network, on a federated basis, on the Web, etc. Practitioners lack dedicated attack trees and threat models to help them consider and tackle the multifaceted attack surface of microservice architectures.

Comprehensive technological references: microservice development entails the use of (heterogeneous) technology stacks, whose combinations and interactions give way to exploits at different levels. These include data leakage due to host-container interactions, threats to encryption reliability due to interacting heterogeneous standards and data-format conversions, as well as surreptitious attacks through software libraries hijacking. Besides the lack of dedicated threat models, there is also a need for concrete references to secure specific technology stacks.

Migration to microservices: several works provide structures and methods to migrate legacy systems to microservices architectures. However, there are no established techniques to elicit the assumptions and invariants (e.g., on shared-memory communication, runtime environment, concurrent/interleaved database accesses, etc.) of the legacy system that the developers of the microservices must deal with—least of all considering how those factors impact the security aspects of the migrated architecture. An additional step in this direction would benefit from following principled security-by-design disciplines.

Global view/control: the distributed nature of microservices makes it difficult to check the correct implementation of architecture-wide security policies, especially when each microservice has a dedicated security configuration. The issue is further exacerbated by the DevOps practice of having different teams deal separately with all aspects of the microservices they develop, including the implementations of their security policies. This fact highlights the need for tools that provide global overviews and guarantees on the security policies, protocols, and invariants of microservice systems.

React & recover techniques: while the literature on preventive and detective measures against attacks abound, little has been done on how microservices should react to attacks and, as a consequence, recover their normal behaviour.

DevSecOps: Agile and DevOps practices are widely used when developing microservices, yet there is no established reference on how these approaches should integrate security in all their aspects (from team culture, management and communication to develop technologies and techniques) and into the lifecycle of microservices.

Fragmentation of outlets: researchers (and practitioners) working on microservices security do not have reference venues (neither journals nor conferences). This has at least two negative consequences. First, it makes it more difficult to gather the relevant work that constitutes the current state-of-the-art of their field—a need to which this study provides a partial solution, in the form of a snapshot of the current field landscape. Second, reference venues work also as gathering and exchange points for researchers to discuss current problems and new ideas, form interest groups, and concretise new contributions and projects to advance the knowledge in the field. Here, our call for action is at the community level, advocating for the establishment of a few reference, high-quality venues able to focus, inform, and orient the agenda of the field.

Regarding the future steps of the line of work of this contribution, we notice that here we focused our investigation on peer-reviewed publications. However, in the general field of microservices (and their security, by extension) the grey literature—which includes non-peer-reviewed reports, working papers, government documents (e.g., those by NIST), white papers—constitutes a relevant body of knowledge that deserves separate studies. As future work, we intend to pursue an activity similar to what we presented in this work, but purposed to investigate the grey literature

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APPENDIX

Dataset and Research Questions in tabular form

We partition the dataset into four tables, each representing the categorisation described in Section 5.2.1— i) Theoretical, ii) Applicative, and iii) Theoretical and Applicative publications and iv) Survey. For each table we have 5 columns. The first 4 columns from the left (after the column containing the reference ("Ref.") to the publication from the publications dataset) and grouped under the column group "Group" report the 4 Research Questions Groups as defined in Section 4. The value shown indicates the amount of questions of each group the publications answered. The last column labeled "Q.Num." presents the number of questions having a positive answer.

Survey Publications

Ref.	G1	G2	G3	G4	Q. Num.
Sultan et al. (2019)	3	2	2	1	2,4,5,8,11,13,14,16
Cerny and Donahoo (2016)	0	0	1	0	13
Westerlund and Kratzke (2018)	0	1	1	1	11,15,16
Bandeira et al. (2019)	0	0	2	0	13,14
Ahmed et al. (2019)	0	1	1	0	8,13
Di Salle et al. (2016)	0	0	1	1	13,16
Bélair et al. (2019)	0	0	2	0	13,14
Márquez and Astudillo (2019)	2	0	2	0	2,4,13,14
Puliafito et al. (2019)	1	0	0	0	2
Manu et al. (2016)	0	2	1	1	8,11,13,17
Lysne et al. (2016)	2	0	1	0	3,4,13
Panduman et al. (2019)	1	0	0	0	2
Casale et al. (2016)	0	0	1	1	13,16
Soldani et al. (2018)	1	1	2	3	4,8,13,14,16-18
Almeida et al. (2017)	1	0	1	0	2,13
Yousefpour et al. (2019)	0	1	1	0	11,13
Trnka et al. (2018)	0	0	1	0	13
Adedugbe et al. (2019)	1	1	2	0	3,8,13,14
Lichtenthäler et al. (2019)	0	1	1	0	11,13
Mohsin and Janjua (2018)	0	1	1	1	11,13,17
Noura et al. (2019)	0	0	1	0	13
Rao et al. (2018)	0	1	1	0	11,13
Yang et al. (2014)	1	1	1	0	3,11,13
Yu et al. (2019)	1	1	2	1	2,8,13,14,16
Casalicchio and Iannucci (2020)	2	1	1	0	2,5,11,13
Plaza et al. (2018)	0	0	0	1	17
Di Francesco et al. (2017)	2	0	0	2	4,5,16,17
Islam et al. (2016)	3	1	0	0	2,4,5,8
Vale et al. (2019)	2	2	0	0	2,5,9,11
Bélair et al. (2019)	0	0	2	0	13,14
Márquez and Astudillo (2019)	2	0	2	0	2,4,13,14
Puliafito et al. (2019)	1	0	0	0	2
Manu et al. (2016)	0	2	1	1	8,11,13,17
Lysne et al. (2016)	2	0	1	0	3,4,13
Panduman et al. (2019)	1	0	0	0	2
Casale et al. (2016)	0	0	1	1	13,16
Soldani et al. (2018)	1	1	2	3	4,8,13,14,16,17,18
Almeida et al. (2017)	1	0	1	0	2,13
Yousefpour et al. (2019)	0	1	1	0	11,13
Sultan et al. (2019)	3	2	2	1	2,4,5,8,11,13,14,16
Ahmed et al. (2019)	0	1	1	0	8,13
Trnka et al. (2018)	0	0	1	0	13
Cerny and Donahoo (2016)	0	0	1	0	13
Ahmadvand et al. (2018)	2	7	3	3	2,3,6-18
Adedugbe et al. (2019)	1	1	2	0	3,8,13,14
Lichtenthäler et al. (2019)	0	1	1	0	11,13
Mohsin and Janjua (2018)	0	1	1	1	11,13,17
Niazi et al. (2018)	0	0	0	0	
Noura et al. (2019)	0	0	1	0	13
Rao et al. (2018)	0	1	1	0	11,13
Yang et al. (2014)	1	1	1	0	3,11,13
Yu et al. (2019)	1	1	2	1	2,8,13,14,16
Casalicchio and Iannucci (2020)	2	1	1	0	2,5,11,13
Plaza et al. (2018)	0	0	0	1	17
Di Francesco et al. (2017)	2	0	0	2	4,5,16,17
Westerlund and Kratzke (2018)	0	1	1	1	11,15,16
Islam et al. (2016)	3	1	0	0	2,4,5,8
Vale et al. (2019)	2	2	0	0	2,5,9,11
Lie et al. (2020)	2	1	0	3	3,4,11,16,17,20
Ali et al. (2020)	4	0	0	0	2,3,4,5
de Sousa et al. (2020)	2	1	1	2	2,3,11,13,16,19
Adam et al. (2020)	2	0	0	0	2,5
Delicato et al. (2020)	3	0	0	0	2,4,5
Mohamed et al. (2020)	2	0	0	1	2,4,18
Waseem et al. (2020)	2	1	2	4	2,4,11,13,14,16-19
Mishra and Otaiwi (2020)	1	1	1	2	2,11,13,16,17
Niknejad et al. (2020)	1	1	0	0	2,11
Moura and Hutchison (2020)	2	0	0	0	2,4
de Araujo Zanella et al. (2020)	4	2	0	0	2,3,4,5,6,7
Mohamed et al. (2020)	2	0	0	1	2,4,18
Razzaq (2020)	2	1	3	4	2,3,11,13-19
Wu et al. (2019)	1	2	0	0	2,6,11

Applicative Publications

Ref.	G1	G2	G3	G4	Q. Num.
George and Mahmoud (2017)	2	0	1	0	2,5,13
Thramboulidis et al. (2019)	1	1	1	0	5,8,13
Ciavotta et al. (2017)	0	1	1	1	11,13,17
Morris (2017)	2	2	1	0	3,5,8,11,13
Fetzer et al. (2017)	2	3	2	1	2,3,6-8,13,14,16
Jita and Pieterse (2018)	1	0	2	0	2,13,14
Perrone and Romano (2017)	0	0	1	1	13,17
Pahl and Aubet (2018)	1	0	2	0	3,13,14
Sialm and Knittl (2016)	0	0	1	0	13
Du et al. (2018)	1	1	1	0	3,8,13
Kalske et al. (2017)	1	1	2	1	2,8,13,14,16
Nehme et al. (2018)	1	1	1	0	2,8,13
Nikoloudakis et al. (2019)	0	2	1	0	8,11,13
Salomoni et al. (2018)	0	0	2	1	13,14,16
Stallenberg and Panichella (2019)	3	1	0	0	2,3,5,7
Morris (2017)	2	2	1	0	3,5,8,11,13
Fetzer et al. (2017)	2	3	2	1	2,3,6,7,8,13,14,16
Jita and Pieterse (2018)	1	0	2	0	2,13,14
Perrone and Romano (2017)	0	0	1	1	13,17
Pahl and Aubet (2018)	1	0	2	0	3,13,14
Sialm and Knittl (2016)	0	0	1	0	13
Cerny and Donahoo (2016)	0	0	1	0	13
Du et al. (2018)	1	1	1	0	3,8,13
Kalske et al. (2017)	1	1	2	1	2,8,13,14,16
Nehme et al. (2018)	1	1	1	0	2,8,13
Nikoloudakis et al. (2019)	0	2	1	0	8,11,13
Salomoni et al. (2018)	0	0	2	1	13,14,16
Stallenberg and Panichella (2019)	3	1	0	0	2,3,5,7
Park and Jeon (2020)	1	1	1	0	2,11,13
Xu and Bian (2020)	0	1	1	1	11,13,16
Brondolin and Santambrogio (2020)	1	2	1	0	2,6,11,13
Ma et al. (2020)	1	1	0	1	3,7,16
Olsthoorn et al. (2020)	1	1	0	1	3,7,16
Chen et al. (2020)	2	1	0	0	2,3,11
Zuo et al. (2020)	2	1	1	0	2,3,11,13
Luntovskyy and Shubyn (2020)	1	3	1	2	2,6,7,11,13,16,19
Ghuge et al. (2020)	3	1	0	0	2,3,4,11
Gerostathopoulos et al. (2020)	1	1	0	0	2,11
Zhang et al. (2020)	1	1	0	0	2,11
Hang et al. (2020)	3	1	0	0	2,3,4,11
Forti et al. (2020)	3	3	1	0	2,3,4,6,7,11,13
Stock et al. (2020)	2	0	0	1	2,4,18
Hasan and Starly (2020)	1	0	1	0	2,13
Kallergis et al. (2020)	2	1	1	0	2,4,11,13
Amir-Mohammadian and Kari (2020)	2	1	0	0	2,4,11
Roca et al. (2020)	3	1	1	0	2,3,4,11,13
Bromberg and Gitzinger (2020)	2	4	1	2	2,3,6-8,11,13,16,18
Jaworski et al. (2019)	2	1	1	0	2,4,11,13

Theoretical Publications (1/3)

Ref.	G1	G2	G3	G4	Q. Num.
ShuLin and JiePing (2020)	3	1	1	0	2,3,4,11,13
Dilshan et al. (2020)	4	1	1	0	2,3,4,5,11,13
Flora (2020)	3	3	1	0	2,3,4,6,7,11,13
Flora et al. (2020)	3	3	0	0	2,3,4,6,7,11
Bogatinovski et al. (2020)	2	0	0	0	2,4
Damis et al. (2020)	3	1	0	0	2,3,4,11
Iraqi and El Bakkali (2020)	3	1	1	0	2,3,4,11,13
Dewanta (2020)	3	1	1	0	2,3,4,11,13
Bumblauskas et al. (2020)	1	0	0	0	2
Giaimo et al. (2020)	2	0	0	2	2,4,16,17
Lenarduzzi et al. (2020)	2	1	1	2	2,4,11,13,16,17
Mann (2020)	3	1	0	1	2,3,4,9,16
Costa et al. (2020)	0	1	1	3	11,13,16,17,18
Fahmideh and Zowghi (2020)	1	0	0	2	2,18,19
Razian et al. (2020)	1	0	0	0	2
Taherizadeh and Grobelnik (2020)	0	1	1	0	11,13
Safaryan et al. (2020)	2	1	0	0	2,4,11
de Toledo et al. (2020)	0	1	1	1	11,13,16
Alulema et al. (2020)	0	1	1	3	11,13,16,17,19
Kapferer and Zimmermann (2020)	0	0	1	2	13,16,19
Redelinghuys et al. (2019)	2	1	0	0	2,3,11
Dash et al. (2020)	2	1	0	0	2,3,11
Kwon et al. (2020)	3	1	0	0	2,3,4,11
Khan and Shameem (2020)	1	1	1	3	2,11,13,16,17,18
DesLauriers et al. (2020)	1	1	1	2	2,11,13,16,17
Bertolino et al. (2020)	0	1	1	1	11,13,16
Di Sanzo et al. (2021)	2	1	0	1	2,4,11,16
Moreira et al. (2020)	2	1	1	2	2,4,11,13,16,17
Li et al. (2019)	2	1	1	0	2,3,11,13

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Theoretical Publications (2/3)

Ref.	G1	G2	G3	G4	Q. Num.
Callegati et al. (2016)	2	4	1	0	3,4,6,7,8,11,13
Preuveneers and Joosen (2019)	1	0	2	1	5,13,14,16
Abidi et al. (2019)	3	1	2	0	3,4,5,8,13,14
Baboi et al. (2019)	0	0	1	0	13
He and Yang (2017)	1	1	0	1	3,11,16
Sim et al. (2019)	0	1	0	0	11
Brito et al. (2019)	1	3	1	0	4,8,11,12,13
Niazi et al. (2018)	0	0	0	1	17
Lu et al. (2017)	3	0	2	0	2,3,5,13,15
Beekman and Porter (2017)	2	0	1	0	2,5,13
Syed and Fernandez (2017)	3	0	2	0	2,4,5,13,15
Syed and Fernandez (2018)	2	0	3	1	2,4,13-16
Bhattacharya (2019)	0	3	1	0	6,7,8,13
Zhang et al. (2017)	0	2	3	0	6,7,13-15
Zaheer et al. (2019)	1	0	1	0	5,13
Walsh and Manferdelli (2017)	0	0	1	0	13
Torkura et al. (2017b)	1	2	2	2	2,6,11,13,14,16,17
Clancy et al. (2019)	0	0	2	0	13,14
Cerny et al. (2018)	0	0	2	2	13,14,18,19
Tourani et al. (2019)	1	3	3	0	3,6,7,8,13-15
Chen et al. (2019)	1	1	1	0	5,8,13
Anisetti et al. (2019)	0	0	1	2	15,16,17
Leite et al. (2019)	0	0	2	2	13,14,16,17
Suneja et al. (2019)	0	2	1	0	8,11,13
Schlossnagle (2018)	0	0	1	2	13,16,17
Schlossnagle (2017)	0	0	1	2	13,16,17
Guija and Siddiqui (2018)	4	0	1	0	2,3,4,5,13
Esparrachiari et al. (2018)	2	0	0	0	2,5
Gupta et al. (2019)	0	0	0	2	16,17
Troiano et al. (2019)	2	0	2	0	2,3,13,14
Tchoubraev and Wiczynski (2015)	0	1	0	0	11
Sun et al. (2015)	2	5	2	0	3,5-8,10,11,13,14
Thanh et al. (2016)	2	3	1	2	2,5,6,7,8,13,16,17
Ahmadvand and Ibrahim (2016)	0	0	1	0	13
Kelbert et al. (2017)	0	0	2	0	13,14
Esposito et al. (2017)	1	0	1	0	2,13
Torkura et al. (2017a)	2	3	1	2	4,5,8,11,12,14,16,17
Yarygina and Bagge (2018)	1	0	1	2	4,13,17,18
Trihinas et al. (2018)	0	0	1	1	13,16
Bánáti et al. (2018)	3	0	2	0	2,3,5,13,14
Pahl et al. (2018)	1	0	1	0	5,13
Diekmann et al. (2018)	0	0	1	1	13,17
Trihinas et al. (2016)	0	0	2	1	13,14,16
Nehme et al. (2019)	0	0	1	2	13,16,17
Torkura et al. (2018)	1	1	1	0	4,8,13
Gerking and Schubert (2019)	1	0	1	0	5,13
Bogner et al. (2019)	0	0	1	4	13,16-19
Petrovska et al. (2019)	2	0	1	0	2,5,14
Osman et al. (2019a)	1	2	2	0	5,6,7,13,14
Chen (2019)	1	1	1	0	4,8,13
Wu et al. (2019)	1	1	1	0	2,11,14
Li et al. (2019)	1	1	0	0	2,11
Mansfield-Devine (2018)	1	1	1	1	4,8,13,16
Trubiani et al. (2018)	3	1	0	1	2,4,5,8,16
Krämer et al. (2019)	1	0	1	0	5,13
Varghese and Buyya (2018)	0	0	1	0	13
Elsayed and Zulkernine (2019)	1	1	1	0	4,8,13
Reyna et al. (2018)	1	0	1	0	2,13
Vaquero et al. (2019)	0	0	1	0	13
Kochovski et al. (2019)	0	0	2	0	13,14
Lwakatare et al. (2019)	0	2	0	2	8,11,16,17
Avritzer et al. (2020)	1	2	0	0	2,6,8
Nagothu et al. (2018)	1	1	0	0	2,11
Baker and Nguyen (2019)	3	2	0	0	2,4,5,9,11
Buzachis and Villari (2018)	1	1	0	0	2,11
Yuan et al. (2019)	0	0	2	0	13,14
Preuveneers and Joosen (2017)	1	0	1	0	5,13
Taha et al. (2019)	1	1	1	0	2,8,13
De Donno et al. (2019)	1	3	2	0	2,8,9,11,13,14
Ghayyur et al. (2018)	0	2	1	0	8,11,13
Xu et al. (2019a)	2	1	1	0	2,3,8,13
Zhiyi et al. (2018)	0	0	1	0	13
Zimmermann (2017b)	0	1	1	3	11,13,16-18
Tien et al. (2019)	2	1	0	0	2,5,6
Oppermann et al. (2018)	0	0	1	0	13
Brucker et al. (2017)	1	0	1	0	5,13
Krishnan et al. (2019)	2	0	2	1	2,5,13,14,17
Salibindla (2018)	1	0	0	0	2
Nguyen and Baker (2019)	1	0	1	0	2,13
Pustchi et al. (2015)	4	1	2	0	2-6,13,15
Westerlund and Kratzke (2018)	0	1	1	1	11,15,16
Garg and Garg (2019)	1	1	0	2	5,11,16,17
Souppaya et al. (2017)	3	3	1	2	2,4,5,8,10,11,13,16,17
Brenner et al. (2017)	0	1	0	0	11
Vassilakis et al. (2016)	0	0	0	0	
Yarygina (2018)	1	3	2	2	2,6,8,11,13,14,16,17
Bozan et al. (2020)	1	0	1	2	2,13,16,17
Cleveland et al. (2020)	1	0	0	0	2
Reed (2020)	1	0	0	0	2
Baarzi et al. (2020)	3	3	1	0	2-,6,7,11,13
Li et al. (2020)	1	1	1	2	2,11,13,16,17
Sundelin et al. (2020)	1	1	0	0	2,11
Sharma et al. (2020)	2	1	1	0	2,5,11,13
Walker and Cerny (2020)	1	1	1	0	2,11,13
Leite et al. (2020)	1	1	1	2	2,11,13,16,17
Russinovich et al. (2021)	3	1	1	3	2,3,4,11,13,16-18
Mohammed and Mohammed (2020)	4	2	0	0	2,3,4,5,6,7
de Oliveira Rosa et al. (2020)	0	1	2	2	11,13,14,16,17
Ke et al. (2020)	2	0	0	0	2,4
Tuma et al. (2020)	3	1	0	0	2,3,4,6
Wieber (2020)	3	1	1	3	2-4,11,13,16-18
Hajek et al. (2020)	3	1	1	0	2,3,4,11,13
Chondamrongkul et al. (2020)	4	1	1	0	2,3,4,5,11,13
Liang and Zhao (2020)	3	1	0	0	2,3,4,11
Liu et al. (2020)	0	1	1	0	11,13
Gorige et al. (2020)	3	1	1	0	2,3,4,11,13
Cerny et al. (2020)	1	1	1	1	2,11,13,18
Tenev and Tsvetanov (2020)	2	1	1	0	2,4,11,13
Jin et al. (2020)	2	1	1	0	2,4,11,13
Wang et al. (2020)	2	1	1	0	2,4,11,13

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Theoretical Publications (3/3)

Ref.	G1	G2	G3	G4	Q. Num.
Badii et al. (2019)	2	2	1	0	3,5,11-13
Yang et al. (2018)	1	1	1	0	4,8,13
Kang et al. (2018)	0	0	2	0	13,14
Casale et al. (2019)	0	0	2	3	13,14,16-18
Di Ciccio et al. (2019)	0	2	1	1	9,10,14,19
Kathiravelu et al. (2019)	0	1	1	0	11,13
Łaskawiec et al. (2019)	0	1	1	0	11,13
Leite et al. (2017)	0	1	1	0	11,13
Redelinghuys et al. (2019)	1	1	1	0	3,8,13
Brambilla et al. (2017)	0	0	1	1	13,19
Shahin et al. (2019)	0	0	1	2	13,16,17
Zimmermann (2017a)	0	0	2	0	13,14
Zimmermann (2017b)	0	1	1	3	11,13,16-18
Tien et al. (2019)	2	1	0	0	2,5,6
Oppermann et al. (2018)	0	0	1	0	13
Brucker et al. (2017)	1	0	1	0	5,13
Krishnan et al. (2019)	2	0	2	1	2,5,13,14,17
Salibindla (2018)	1	0	0	0	2
Nguyen and Baker (2019)	1	0	1	0	2,13
Pustchi et al. (2015)	4	1	2	0	2-6,13,15
Garg and Garg (2019)	1	1	0	2	5,11,16,17
Souppaya et al. (2017)	3	3	1	2	2,4,5,8,10,11,13,16,17
Brenner et al. (2017)	0	1	0	0	11
Vassilakis et al. (2016)	2	0	0	0	2,4
Yarygina (2018)	1	3	2	2	2,6,8,11,13,14,16,17
Beekman and Porter (2017)	2	0	1	0	2,5,13
Syed and Fernandez (2017)	3	0	2	0	2,4,5,13,15
Syed and Fernandez (2018)	2	0	3	1	2,4,13,14,15,16
Bhattacharya (2019)	0	3	1	0	6,7,8,13
Zhang et al. (2017)	0	2	3	0	6,7,13,14,15
Zaheer et al. (2019)	1	0	1	0	5,13
Walsh and Manferdelli (2017)	0	0	1	0	13
Torkura et al. (2017b)	1	2	2	2	2,6,11,13,14,16,17
Clancy et al. (2019)	0	0	2	0	13,14
Cerny et al. (2018)	0	0	2	2	13,14,18,19
Tourani et al. (2019)	1	3	3	0	3,6,7,8,13,14,15
Chen et al. (2019)	1	1	1	0	5,8,13
Anisetti et al. (2019)	0	0	1	2	15,16,17
Leite et al. (2019)	0	0	2	2	13,14,16,17
Suneja et al. (2019)	0	2	1	0	8,11,13
Schlossnagle (2018)	0	0	1	2	13,16,17
Schlossnagle (2017)	0	0	1	2	13,16,17
Guija and Siddiqui (2018)	4	0	1	0	2,3,4,5,13
Esparrachiari et al. (2018)	2	0	0	0	2,5
Gupta et al. (2019)	0	0	0	2	16,17
Troiano et al. (2019)	2	0	2	0	2,3,13,14
Tchoubraev and Wiczynski (2015)	0	1	0	0	11
Sun et al. (2015)	2	5	2	0	3,5,6,7,8,10,11,13,14
Callegati et al. (2016)	2	4	1	0	3,4,6,7,8,11,13
Thanh et al. (2016)	2	3	1	2	2,5,6,7,8,13,16,17
Ahmadvand and Ibrahim (2016)	0	0	1	0	13
Kelbert et al. (2017)	0	0	2	0	13,14
George and Mahmoud (2017)	2	0	1	0	2,5,13
Esposito et al. (2017)	1	0	1	0	2,13
Torkura et al. (2017a)	2	3	1	2	4,5,8,11,12,14,16,17
Yarygina and Bagge (2018)	1	0	1	2	4,13,17,18
Trihinas et al. (2018)	0	0	1	1	13,16
Bánáti et al. (2018)	3	0	2	0	2,3,5,13,14
Pahl et al. (2018)	1	0	1	0	5,13
Diekmann et al. (2018)	0	0	1	1	13,17
Trihinas et al. (2016)	0	0	2	1	13,14,16
Nehme et al. (2019)	0	0	1	2	13,16,17
Torkura et al. (2018)	1	1	1	0	4,8,13
Gerking and Schubert (2019)	1	0	1	0	5,13
Bogner et al. (2019)	0	0	1	4	13,16,17,18,19
Petrovska et al. (2019)	2	0	1	0	2,5,14
Osman et al. (2019a)	1	2	2	0	5,6,7,13,14
Preuveneers and Joosen (2019)	1	0	2	1	5,13,14,16
Chen (2019)	1	1	1	0	4,8,13
Wu et al. (2019)	1	1	1	0	2,11,14
Li et al. (2019)	1	1	0	0	2,11
Ruan et al. (2019)	0	0	0	0	
Mansfield-Devine (2018)	1	1	1	1	4,8,13,16
Baboi et al. (2019)	0	0	1	0	13
Trubiani et al. (2018)	3	1	0	1	2,4,5,8,16
Krämer et al. (2019)	1	0	1	0	5,13
Varghese and Buyya (2018)	0	0	1	0	13
Elsayed and Zulkernine (2019)	1	1	1	0	4,8,13
Reyna et al. (2018)	1	0	1	0	2,13
Vaquero et al. (2019)	0	0	1	0	13
Kochovski et al. (2019)	0	0	2	0	13,14
Lwakatare et al. (2019)	0	2	0	2	8,11,16,17
Avritzer et al. (2020)	1	2	0	0	2,6,8
Nagothu et al. (2018)	1	1	0	0	2,11
Baker and Nguyen (2019)	3	2	0	0	2,4,5,9,11
Buzachis and Villari (2018)	1	1	0	0	2,11
Yuan et al. (2019)	0	0	2	0	13,14
Preuveneers and Joosen (2017)	1	0	1	0	5,13
Taha et al. (2019)	1	1	1	0	2,8,13
He and Yang (2017)	1	1	0	1	3,11,16
Sultan et al. (2019)	3	2	2	1	2,4,5,8,11,13,14,16
De Donno et al. (2019)	1	3	2	0	2,8,9,11,13,14
Ghayyur et al. (2018)	0	2	1	0	8,11,13
Zhiyi et al. (2018)	0	0	1	0	13
Sim et al. (2019)	0	0	0	0	
Xu et al. (2019a)	2	1	1	0	2,3,8,13
Badii et al. (2019)	2	2	1	0	3,5,11,12,13
Yang et al. (2018)	1	1	1	0	4,8,13
Di Salle et al. (2016)	0	0	1	1	13,16
Kang et al. (2018)	0	0	2	0	13,14
Brito et al. (2019)	1	3	1	0	4,8,11,12,13
Casale et al. (2019)	0	0	2	3	13,14,16,17,18
Di Ciccio et al. (2019)	0	2	1	1	9,10,14,19
Kathiravelu et al. (2019)	0	1	1	0	11,13
Łaskawiec et al. (2019)	0	1	1	0	11,13
Leite et al. (2017)	0	1	1	0	11,13
Redelinghuys et al. (2019)	1	1	1	0	3,8,13
Brambilla et al. (2017)	0	0	1	1	13,19
Shahin et al. (2019)	0	0	1	2	13,16,17
Zimmermann (2017a)	0	0	2	0	13,14
Zdun et al. (2019)	0	1	1	2	11,13,16,19

Theoretical and Applicative Publications

Ref.	Group				Q. Num.
	G1	G2	G3	G4	
Ahmadvand et al. (2018)	2	7	3	3	2,3,6-18
Forti et al. (2020)	0	0	2	0	13,14
Díaz-Sánchez et al. (2019)	2	1	1	0	4,5,11,13
Han et al. (2019)	3	1	1	0	2,3,5,9,13
Paladi et al. (2018)	2	4	2	1	2,4,6,8,9,12,13,14,17
Stocker et al. (2018)	2	2	1	0	2,5,8,12,13
Andersen et al. (2018)	3	2	2	0	2,3,4,8,11,13,14
Andersen et al. (2018)	3	2	2	0	2,3,4,8,11,13,14
Li et al. (2018)	4	5	3	2	2-9,11,13-15,18,19
Akkermans et al. (2018)	1	3	2	0	3,6,7,9,13,14
Nikouei et al. (2019)	1	1	2	0	5,8,13,14
Nagendra et al. (2019)	4	1	1	0	2-6,13
Wang et al. (2018)	2	0	0	1	2,3,16
Basso et al. (2017)	1	1	1	0	2,9,13
Marchal et al. (2018)	2	0	2	0	2,3,13,14
Demoulin et al. (2018)	3	0	0	0	2,3,5
Pahl and Donini (2018)	1	0	2	1	5,13,14,20
Kang et al. (2019)	2	1	2	1	3,4,8,13,14,17
Osman et al. (2019b)	0	0	0	1	17
Xu et al. (2019b)	2	1	1	1	2,3,11,13,18
da Silva et al. (2019)	2	1	0	0	2,4,9
Jin et al. (2019)	3	1	0	0	2,3,4,12
Wen et al. (2019)	2	2	0	0	3,4,8,12
Callegati et al. (2018)	3	1	2	0	2,4,5,8,13,14
Jander et al. (2018)	2	1	1	2	2,3,11,13,16,20
Jander et al. (2019)	2	1	1	1	2,3,11,13,20
Surantha and Ivan (2019)	3	1	1	1	3-5,10,13,20
Hole (2016)	4	2	3	1	2,3,4,5,8,11,13-15,16
Ravichandran et al. (2016)	4	1	2	2	2-5,8,13,14,16,17
Otterstad and Yarygina (2017)	2	3	2	1	2,3,6,7,8,13,14,17
Yarygina and Otterstad (2018)	1	3	2	0	3,6,7,8,13,14
Luo et al. (2018)	0	1	3	3	8,13-18
Camilli et al. (2017)	2	1	3	4	2,3,8,13-19
Nkomo and Coetzee (2019)	3	3	3	1	2,3,5,8,9,11,13-15,17
Beheshti et al. (2019)	0	1	2	0	9,13,14
Chidambaram et al. (2019)	2	0	1	0	3,5,13
Jan et al. (2019)	1	3	1	0	5,6,7,8,14
Melis et al. (2018)	1	1	2	0	3,12,13,14
Paschke (2016)	2	0	2	0	2,3,13,14
Prandi et al. (2019)	0	0	1	0	13
Ibrahim et al. (2019)	3	0	1	2	2,3,4,13,16,17
Ranjbar et al. (2017)	2	0	1	0	2,3,13
Han et al. (2019)	3	1	1	0	2,3,5,9,13
Paladi et al. (2018)	2	4	2	1	2,4,6,8,9,12-14,17
Stocker et al. (2018)	2	2	1	0	2,5,8,12,13
Andersen et al. (2018)	3	2	2	0	2,3,4,8,11,13,14
Li et al. (2018)	4	5	3	2	2-9,11,13-15,18,19
Akkermans et al. (2018)	1	3	2	0	3,6,7,9,13,14
Nikouei et al. (2019)	1	1	2	0	5,8,13,14
Nagendra et al. (2019)	0	0	0	0	
Wang et al. (2018)	2	0	0	1	2,3,16
Basso et al. (2017)	1	1	1	0	2,9,13
Marchal et al. (2018)	2	0	2	0	2,3,13,14
Demoulin et al. (2018)	3	0	0	0	2,3,5
Pahl and Donini (2018)	1	0	2	1	5,13,14,20
Kang et al. (2019)	2	1	2	1	3,4,8,13,14,17
Osman et al. (2019b)	0	0	0	1	17
Xu et al. (2019b)	2	1	1	1	2,3,11,13,18
da Silva et al. (2019)	2	1	0	0	2,4,9
Jin et al. (2019)	3	1	0	0	2,3,4,12
Wen et al. (2019)	2	2	0	0	3,4,8,12
Abidi et al. (2019)	3	1	2	0	3,4,5,8,13,14
Callegati et al. (2018)	3	1	2	0	2,4,5,8,13,14
Thramboulidis et al. (2019)	1	1	1	0	5,8,13
Jander et al. (2018)	2	1	1	2	2,3,11,13,16,20
Jander et al. (2019)	2	1	1	1	2,3,11,13,20
Surantha and Ivan (2019)	3	1	1	1	3,4,5,10,13,20
Ciavotta et al. (2017)	0	1	1	1	11,13,17
Díaz-Sánchez et al. (2019)	2	1	1	0	4,5,11,13
Hole (2016)	4	2	3	1	2-5,8,11,13-16
Ravichandran et al. (2016)	4	1	2	2	2-5,8,13,14,16,17
Otterstad and Yarygina (2017)	2	3	2	1	2,3,6,7,8,13,14,17
Yarygina and Otterstad (2018)	1	3	2	0	3,6,7,8,13,14
Luo et al. (2018)	0	1	3	3	8,13,14,15,16,17,18
Camilli et al. (2017)	2	1	3	4	2,3,8,13,14,15,16,17,18,19
Ahmadvand et al. (2018)	2	7	3	3	2,3,6-18
Nkomo and Coetzee (2019)	3	3	3	1	2,3,5,8,9,11,13-15,17
Beheshti et al. (2019)	0	1	2	0	9,13,14
Chidambaram et al. (2019)	2	0	1	0	3,5,13
Jan et al. (2019)	1	3	1	0	5,6,7,8,14
Melis et al. (2018)	1	1	2	0	3,12,13,14
Paschke (2016)	2	0	2	0	2,3,13,14
Prandi et al. (2019)	0	0	1	0	13
Ibrahim et al. (2019)	3	0	1	2	2,3,4,13,16,17
Ranjbar et al. (2017)	2	0	1	0	2,3,13
Ranawaka et al. (2020)	2	1	1	0	2,3,11,13
Du et al. (2020)	2	1	2	0	2,3,11,13,15
Haque et al. (2020)	4	1	1	2	2,3,4,5,11,13,16,17
Avritzer et al. (2020)	3	4	1	4	2-4,6,7,9,11,13,16-19
Alaluna et al. (2020)	3	1	0	0	2,3,4,11
Falah et al. (2020)	1	1	0	0	2,6
Truong and Klein (2020)	2	1	1	1	2,4,11,13,16
Nikolakis et al. (2020)	3	1	2	0	2,3,4,11,13,14
Kumar and Goyal (2020)	2	4	2	3	2,4,6,7,8,11,13,14,16,17,18
Janjua et al. (2020)	3	1	1	1	2,3,4,11,13,20
Hahn et al. (2020)	3	4	1	1	2,3,4,8,9,10,11,13,16
Cheruvu et al. (2020)	2	0	0	0	2,3
Lakhan and Li (2020)	0	1	1	0	11,13
Javed et al. (2020)	2	0	1	0	3,4,13
Lou et al. (2020)	4	4	0	0	2,3,4,5,6,7,10,11
Maati and Saidouni (2020)	4	0	0	0	2,3,4,5
Lu et al. (2021)	2	1	0	2	2,3,11,18,19
Copei et al. (2020)	3	1	1	1	2,4,5,11,13,20
Ranawaka et al. (2020)	2	1	1	0	2,3,11,13