Architectures of Cloud-enabled Cyber Physical Systems — a Systematic Mapping Study

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Architectures of Cloud-enabled Cyber Physical Systems — a Systematic Mapping Study

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***Abstract*—Cloud enabled Cyber Physical Systems (CCPS) combine embedded systems with highly scalable cloud services. Such systems provide opportunities to offload computing or data analytics tasks which require more resources than an embedded device can offer. The development of a CCPS involves multiple stakeholders as well as engineers and developers from different disciplines, which makes the description and communication of the system architecture a challenging task. Additionally, the architecture design of CCPS has the inherent challenge to determine which functionality should be placed on the device, in the cloud, or on a possible fog/edge device within or close to the system. This systematic mapping study evaluates how CCPS architectures are discussed in the current literature and which topics are associated with cloud computing in CCPS architectures. The results show a significant increase in CCPS publications over the last years, a focus on a specific architectural viewpoint and application areas, and a potential misalignment with the common understanding of cloud computing as a paradigm.**

***Index Terms*—Cyber-physical systems; Cloud computing; Fog/Edge computing; Internet of Things**

I. Introduction

Recent trends like Internet of Things, Smart Home, Smart Factory and Cloud Robotics constitute systems which combine embedded systems with powerful computing and storage resources in the cloud. Such systems comprise challenges as well as opportunities, since the capabilities and restrictions of embedded systems and cloud computing services are fundamentally different. More specifically, embedded systems have constricted memory and computing capacity and often need to react in real time. Cloud computing services on the other hand provide almost unlimited resources, but are subject to network latency [1].

Since the involved technologies in CCPS cover the whole range from embedded device to cloud services, the engineers and developers involved have different expertise and therefore a different way to look at and describe a system. Additionally, there are many different stakeholders involved in maintaining and using a CCPS [2]. To form a coherent system, it is therefore necessary to describe the system architecture in a way that covers the interlacing system areas and provides a consistent understanding of the system architecture among the stakeholders.

Leveraging the resources of all components of the system to ensure a stable and efficient CCPS requires a carefully designed software architecture. The architecture design needs to take the requirements and constraints from all the involved components and stakeholders into account. This process also involves decisions about which functionality should be implemented in which part of the system. Concepts like fog and edge computing play an important role in CCPS since they offer a way to bridge the gap between embedded systems and cloud computing [3].

An overview of how CCPS architectures are described in the literature can provide a crucial starting point for CCPS architecture description and system development. Towards this direction, a survey focusing on mobile robots, wireless sensor networks and vehicular networks as different kinds of CCPS has been provided in [1] and a systematic mapping study discussing cyber-physical systems in Industry 4.0 was presented in [4]. However, both of these works focus on specific application areas and do not provide a systematic overview of the research on CCPS architectures. Furthermore, the preliminary study on architecting cyber-physical systems provided in [5] did not focus on cloud-enabled cyber-physical systems and was conducted on a limited data set. In the absence, to the extent of our knowledge, of other systematic studies in the area, we therefore opt to perform a systematic mapping study [6] of the literature on CCPS architecting.

More specifically, this systematic mapping study examines current publications on CCPS architectures with two aims. The first is to identify current trends and common approaches to design and communicate the architecture of CCPSs. The second aim is to identify common topics associated with the usage of cloud computing within CCPS architectures.

The next section will provide some background information on the concepts discussed in this paper. Section III presents the study protocol. Obtained results are presented in Section IV and discussed in Section V as starting points of future work. Section VI provides the conclusions of this study.

II. Background

In order to provide the necessary context for the non-expert readers, in the following we briefly discuss the key concepts for this study, i.e. CPS and CCPS, cloud computing, and the related terms edge and fog computing. We also introduce the set of architectural viewpoints from the literature that will be used in the next section to characterize the architectures presented in the related studies.

Rajkumar et al. provide the following definition for CPS: "Cyber-physical systems (CPS) are physical and engineered systems whose operations are monitored, coordinated, controlled and integrated by a computing and communication core" [7]. Such systems can be found in various application areas like health care, industrial machinery, automotive and many more. Some CPS have become an integral part of our every day life. For example a modern vehicle can be regarded as a CPS, since the control units within the vehicle monitor, coordinate and control the operations of the vehicle.

Some CPS also incorporate functionalities from cloud services, integrating components from the whole bandwidth of technology layers. A variety of terms have been created to describe this category of systems, eg. cyber-physical cloud computing, cloud-integrated CPS or cloud-based CPS [2]. Within this study, the term cloud enabled cyber-physical systems (CCPS) will be used as an umbrella term for all these terms. It needs to be noted here that for the purposes of this mapping study the CCPS term is only used for our own organizational purposes. As discussed in the following section, the search for related studies aims to identify any CPS with a cloud component, irrespective of what term is used to describe the system.

The integration of cloud computing complements embedded resources with highly scalable cloud resources, enabling computation offloading of complex tasks and the collection of big data for analysis [1]. Examples of such systems are a cyber-physical speech-controlled wheelchair as presented in [8], a location-based mobile crowd-sensing framework as discussed in [9] or an industrial cyber-physical system for condition-based monitoring in manufacturing processes [10].

Since there have been many different definitions of what constitutes cloud computing in the literature, for the purposes of this work we use the one published by the NIST [11] as a reference point. The definition of cloud computing from the NIST lists on-demand self-service, broad network access, resource pooling, rapid elasticity and measured service as the five essential characteristics of cloud computing. It also defines the cloud service models Software as a Service (SaaS), Platform as a Service (PaaS) and Infrastructure as a Service (IaaS) and the delivery models private cloud, community cloud, public cloud and hybrid cloud [11]. In this study we investigate how the included publications align themselves with this definition, since it is the de facto standard for cloud computing in both academia and industry.

Edge and fog computing architectures can be used to bridge the gap between embedded systems and cloud services. They address issues regarding the latency between embedded and cloud resources. In edge computing, devices on the edge are used for computational tasks, while fog computing adds a complementary layer between edge devices and cloud. This way, different levels of computation from low latency but resource restricted edge devices over medium latency and less restricted fog or edge nodes to latency sensitive but nearly unrestricted cloud resources can be created within one system [3].

Finally, the C-MobILE[1] reference architecture proposed a set of six core viewpoints in order to provide a structured architectural description of CPS: Context, Physical, Functional, Communication, Information and Implementation. These viewpoints are based on existing literature and other reference architectures [12], [13]. More specifically, the Context viewpoint focuses on the relationships, dependencies and interactions between the system and its environment, while the Physical viewpoint describes the hardware environment that the system needs as well as the technical requirements for each elements. Functional elements, their responsibilities, interfaces and primary interactions are described in the Functional viewpoint. In the communication viewpoint, the focus is on the communication between subsystems deployed on different hardware. The Information viewpoint describes how information is stored, managed and distributed in the architecture. Details on the implementation of the functionality into a real life software system are described in the Implementation viewpoint [12]. This study uses the proposed viewpoints to classify the architecture visualizations provided by the retrieved publications.

III. Method

This study was conducted as a systematic mapping study following the guidelines proposed by Petersen et al. [6]. The following subsections discuss the study design by providing more details on the formulated research questions, the search process, the study selection, and the data extraction process.

A. Research Questions

The goal of this mapping study is to identify trends, approaches, and the adoption of cloud computing in current research on architecting Cloud enabled Cyber Physical Systems (CCPSs). Focusing on the description of the designed architectures as well as the usage of cloud computing in the discussed CCPSs led to the following research questions:

- RQ1: What are the trends in CCPS architecture-related research?
- RQ2: From which viewpoint are the architectures of CCPS described in the literature?
- RQ3: How is cloud computing discussed in the publications?
  - RQ3.1: Which cloud-defining terms appear in the paper?
  - RQ3.2: What common topics are associated with cloud computing in CCPS?

The first research question (RQ1) aims to identify the general trends in the published research on CCPS over the recent years in terms of publication venues, types, and topics. In the second research question (RQ2), the focus is on the

[1] https://c-mobile-project.eu

TABLE I
SEARCH STRINGS FOR DATABASE SEARCH

Database	**Search String**
ACM Digital Library	recordAbstract:(+cyber +physical +system +cloud +computing +architecture)
IEEE Xplore	("Abstract":cyber AND physical AND system AND cloud AND computing AND architecture)
Scopus	ABS(cyber AND physical AND system AND cloud AND computing AND architecture)
Web of Science	TS=(cyber AND physical AND system AND cloud AND computing AND architecture)
Wiley Online Library	cyber AND physical AND system AND cloud AND computing AND architecture

visual architecture representations and the viewpoints they provide on the presented systems. Since the architecting of CCPS involves stakeholders from multiple disciplines, the architecture description is critical for a unified understanding of the architecture across disciplines. The provided architectural viewpoints are an indication of which perspectives are deemed the most important for publications.

RQ3 is directed towards the discussion of cloud computing within CCPS publications. The first focus point lies on the usage of cloud defining terms. For this purpose, this work investigates whether the publications align themselves to the most commonly accepted definition of cloud computing, i.e. the one provided by the NIST [11]. The degree of alignment will be determined by analyzing whether the publications refer to [11] and/or they refer to the common deployment and delivery models defined by [11] as discussed in the previous section. The second focus point of RQ3 is to analyze which topics are commonly associated with cloud computing in CCPS.

B. Search

A search was performed in five online databases: ACM Digital Library, IEEE Xplore Digital Library, Scopus, Web of Science, and Wiley Online Library. The research questions were transformed into search strings following the PICO (Population, Intervention, Comparison and Outcomes) approach suggested by Kitchenham and Charters [14]. In the context of this study, the *population* included publications in the intersection of *the cyber physical system domain* and the *cloud computing domain*, with *architecture* as *intervention*. Although no empirical *comparison* was made, the *different ways to describe the proposed architectures* were collected to identify common approaches. *No outcomes* are formulated since there was no qualitative evaluation of the investigated architectures.

The search strings for the individual databases are shown in Table I; Table II lists the number of search results which were obtained per database. In order to scope the retrieved references to the most relevant studies, the search was limited to the abstract via the corresponding search parameters in the five databases. *Cloud computing* was intentionally used as a term instead of the simpler 'cloud' since a pilot search returned a significant number publications unrelated to cloud computing. These publications contained unrelated terms like "point cloud" that affected the efficacy of the search.

C. Study Selection

Relevant publications for this study had to be peer reviewed and to discuss an architecture of a cyber physical system with a cloud component, which led to the following inclusion criteria:

- The publication is peer reviewed;
- At least one visual representation of the CCPS architecture is provided.

The following exclusion criteria were defined:

- Full text of the publication is not available;
- Publications in languages other than English.

Do notice that secondary studies are not excluded by default by these criteria. This is because many secondary studies in the field appear to contain architectural diagrams, either original or citing surveyed work, and mentions to cloud providers and services that are relevant for our purposes. The process applied for study selection was to first de-duplicate the search results, then apply the exclusion criteria and afterwards apply the inclusion criteria. 235 publications were selected for inclusion in this study after the end of this process. An overview of the number of results obtained during each step is given in Figure 1 and the references for the obtained and included publications are available on Github[2]. Study selection was done by the first author; the included studies were checked by the second author during data extraction for the elimination of any possible false positives.

TABLE II
NUMBER OF STUDIES PER DATABASE

Databases	**Search Results**
ACM Digital Library	68
IEEE Xplore	220
Scopus	190
Web of Science	105
Wiley	10

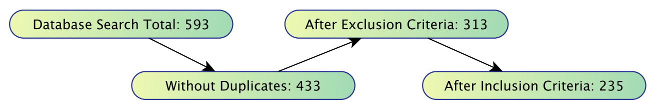

Fig. 1. Number of obtained publications during study selection steps.

D. Data Extraction

The data extraction was performed by aggregation of the meta data provided by the research databases and by coding in Atlas.ti[3]. Table III lists the extracted data fields with

[2]https://github.com/search-rug/sms-on-ccps
[3]https://atlasti.com

TABLE III
EXTRACTED DATA ITEMS

Item	Extraction Method	Relevant RQ
Title Year Venue	Metadata	RQ1
Architectural Viewpoints	Manual Coding	RQ2
SaaS PaaS IaaS	Automatic Coding	RQ3.1
Private Cloud Public Cloud Community Cloud	Automatic Coding	RQ3.1
NIST definition	Automatic Coding	RQ3.1
Amazon Google Microsoft IBM	Automatic Coding	RQ3.1
fog edge IoT SoS	Automatic Coding	RQ3.1
cloud paragraphs	Automatic Coding	RQ1, RQ3.2

the corresponding extraction method and the related research questions. Architectural viewpoints were coded manually for each visual architecture representation in the publications. To reduce bias, the coding was done by the first and second author independently, and conflicts in the applied codes were resolved by a discussion between the authors to create a consensus.

The assignment of cloud term-related codes as well as the extraction of common cloud phrases was achieved through automated coding. Cloud related terms that were chosen for coding are the cloud delivery and deployment models from the NIST definition, the NIST definition itself (as a reference), and the names of major cloud providers like Amazon Web Services (AWS). The terms edge, fog, IoT and SoS were also added to the codes to investigate the relevance of these terms for CCPS architectures. Each of the automatically applied codes was applied on document level, meaning that each publication that contained the term at least once was coded with it.

In order to determine which topics are discussed in relation to cloud computing in CCPS, all paragraphs containing the word 'cloud' were extracted from the publications to create a text corpus. Within the created text corpus, the most frequent noun phrases of size n=2 were extracted. From this set, the obvious cloud related phrases (e.g. cloud service, cloud provider) as well as non relevant English phrases (e.g. other hand) were removed. A text corpus that was created by extracting all sentences with the word 'cloud' led to the same outcome as the extraction on paragraph level. Further examination led to the observation that the publications tend to use the word cloud in every sentence of the paragraphs which discuss cloud computing. The extracted topics were used for answering both RQ3.2 and for providing a better view of the trends in publications (RQ1), as discussed in the following.

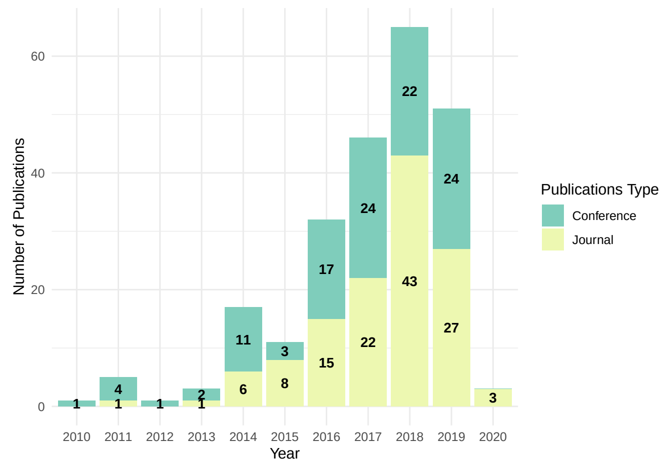

Fig. 2. Publications per Year.

TABLE IV
VENUES WITH MORE THAN TWO PUBLICATIONS

Venue	# Publications
IEEE Access	21
Future Generation Computer Systems	7
Sensors (Switzerland)	6
IEEE Industrial Cyber-Physical Systems (ICPS)	5
IEEE Int. Conf. on Em. Tech. and Fact. Aut. (ETFA)	4
Concurrency and Computation	3
IEEE Internet of Things Journal	3
IEEE Systems Journal	3
IEEE Wireless Communications	3
Int. Journal of Advanced Manufacturing Technology	3
Int. Journal of Computer Integrated Manufacturing	3

IV. RESULTS

RQ1: The distribution of publications over the years summarized by Fig. 2 shows a significant increase in the number of publications on CCPSs over the last years. In particular the number of publications in journals has steadily increased with a peak in 2018 in which journal publications were almost double than conference publications. The first retrieved publication on the subject appears in 2010.

In the selected set of publications there is a total of 165 venues, among which 132 venues only feature one, and 21 venues which feature two publications on the topic of CCPS architecture. Table IV lists all venues with three or more publications on CCPS architecture. The IEEE Access open access journal for multidisciplinary research dominates the list.

RQ2: As shown in Fig. 3, the Physical viewpoint is by far the preferred viewpoint for architectural visualizations in CCPS, appearing in 269 architectual visualizations. It is followed by the Functional and Communication viewpoints. The Context viewpoint is the least frequently chosen viewpoint for CCPS architectures after excluding visualizations where the viewpoint was deemed unclear by both coders, with only 48 architectural visualizations using it.

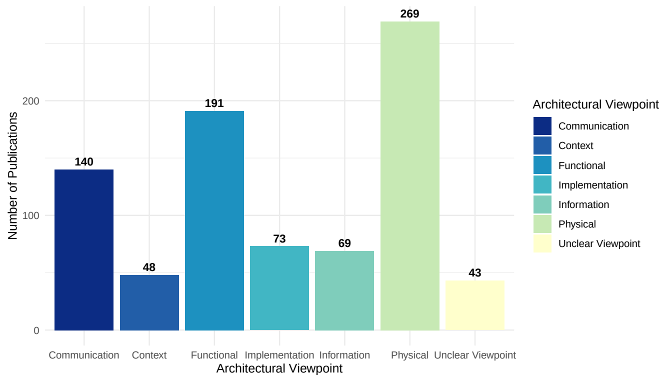

Fig. 3. Total Number of Architecture Visualizations per Architectural Viewpoint.

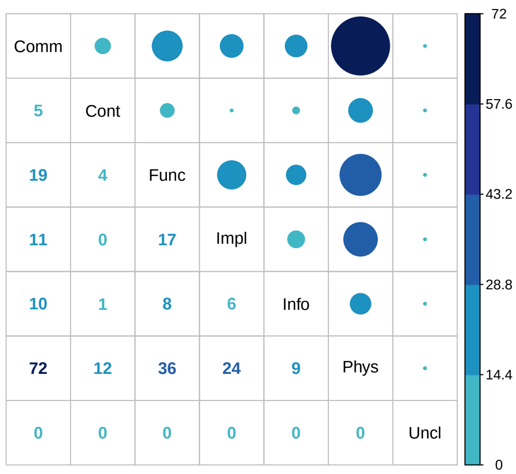

Fig. 4. Combinations of Architectural Viewpoints within one Architecture Visualization as a correlation diagram.

Many publications combine multiple viewpoints within one figure. Figure 4 shows the frequency of viewpoint combinations within one architecture visualization. The three most frequent viewpoint combinations are between the Physical on the one hand, and the Communication (72 occurrences), Functional (36), and Implementation (24) viewpoints on the other. Among the other viewpoints, the Communication and Functional (19), as well as the Functional and Implementation (17) are the most popular combinations.

Publications often also provide multiple architecture visualizations to describe a CCPS, with an average of 3.5 visualizations per paper. Figure 5 provides an overview over the chosen architectural viewpoints based on the amount of distinct architectural viewpoints appearing in each publication, that is, use of a viewpoint is only counted once per paper. As it can be seen in the figure, most publications depict architectures from two or three distinct viewpoints. In the cases where only one or two viewpoints are depicted, there is a clear preference for the Physical viewpoint, with the Functional viewpoint

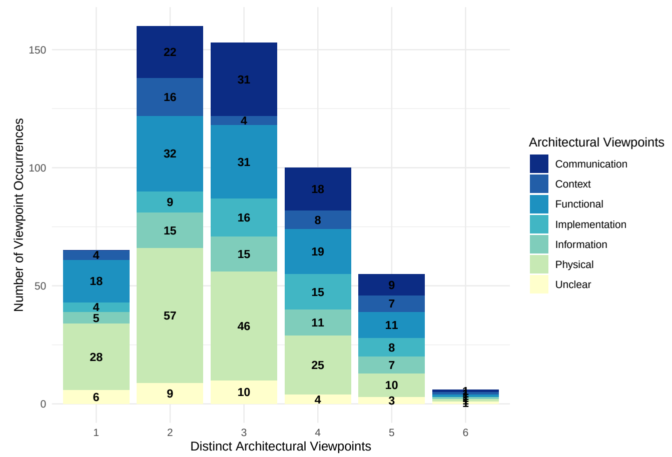

Fig. 5. Distribution of distinct Architectural Viewpoints across publications.

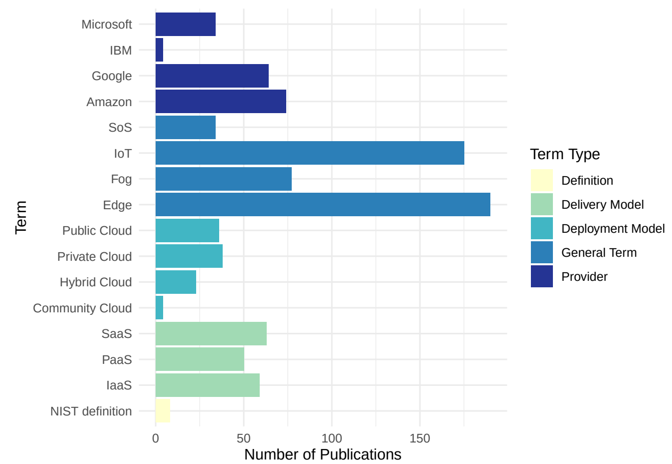

Fig. 6. Number of Publications containing Controlled Terms.

as second most frequently chosen option. This preference correlates with the total number of architectural visualizations per architectural viewpoint given in Fig. 3.

RQ3: Figure 6 shows the cloud related and other controlled terms which were mentioned in the publications. Only eight (!) studies reference the NIST definition of cloud computing. Despite that, delivery models are mentioned in approximately a quarter of the 235 publications: IaaS was mentioned in 59, PaaS in 50, and SaaS in 63 publications. Deployment models were mentioned less often than delivery models, with public and private cloud being the most commonly mentioned models. Regarding cloud providers, Amazon (Web Services — AWS) was the most frequently mentioned provider, followed by Google (Cloud Platform).

The most striking result among the rest of the controlled terms is that the terms edge and IoT are used far more often than the cloud related terms, with edge being mentioned in 190 (81%) and IoT being mentioned in 175 (74.5%) publications. Fog is mentioned as a term in almost 33% (77) and SoS in 14% (34) of the publications (RQ3.1).

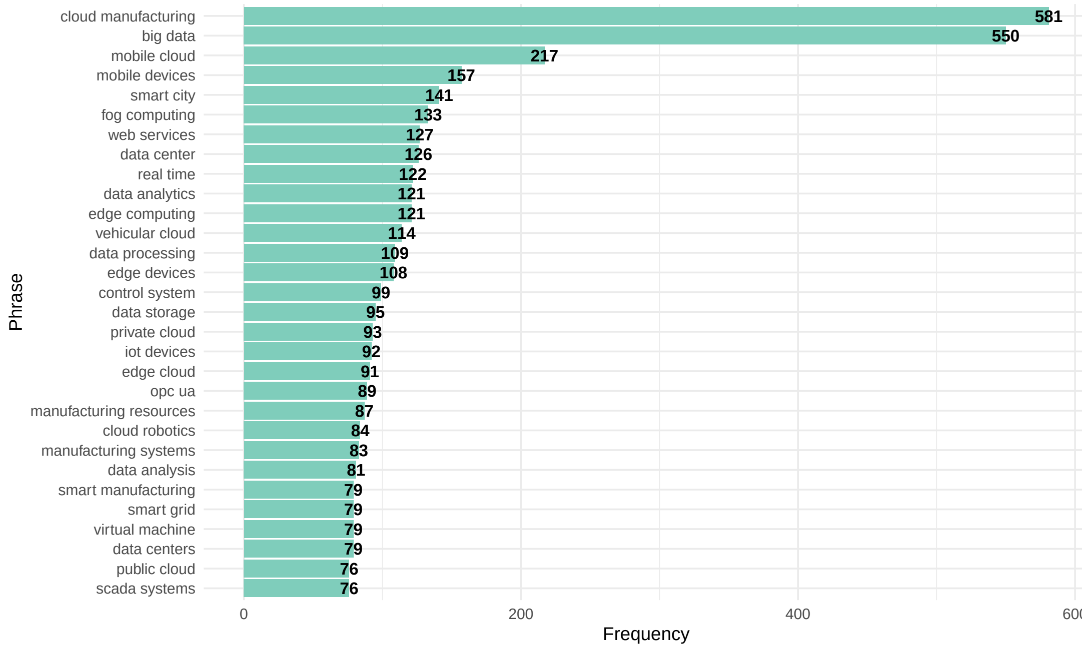

Fig. 7. Common phrases in cloud paragraphs.

With respect to RQ3.2, Fig. 7 shows the thirty most frequent phrases extracted from paragraphs containing the word cloud. The most prominent phrases in those paragraphs are 'cloud manufacturing' and 'big data' with 581 and 550 occurrences in total, respectively. Among the collected phrases, there are common *application areas* like cloud manufacturing, with terms like manufacturing resources, manufacturing systems and smart manufacturing, mobile cloud / mobile devices, smart city, vehicular cloud, cloud robotics and smart grid. Another category among the collected phrases is centered around *data*, with phrases like big data, data center, data analytics, data processing, data storage and data analysis. Terms from the *fog, edge and IoT* area are also common with phrases like fog computing, edge computing, edge devices, IoT devices and edge cloud. Other categories of terms commonly mentioned are *system components* (eg. web services, control system), *deployment details* (virtual machine, private cloud) and *industry standards* like OPC UA[4] and SCADA systems [15].

Returning now briefly to RQ1: The extracted application areas discussed in the previous paragraph potentially provide interesting information on the trends in CCPS architecture development. In order to further investigate these trends and determine the distribution of the application areas over the years, an additional automatic annotation was done for the included publications. The previously collected application area phrases were used as controlled terms for the annotation process, which followed the same steps as the annotation with cloud related terms discussed earlier.

Figure 8 shows the distribution of the mentioned application areas within the publications over the years. The most frequently mentioned application areas are smart grid and mobile cloud followed by smart city and cloud manufacturing. Both smart grid and mobile cloud reached a peak in the number of publications in the year 2018.

[4]https://opcfoundation.org/about/opc-technologies/opc-ua/

V. Discussion

A. Trends in CCPS architecture-related research

The fast increasing number of publications indicates an increasing interest in CCPS architectures. Furthermore, the significant increase in the number of journal publications provides evidence of a quickly maturing field of research. However it needs to be seen if the observed peak in 2018 is simply the result of executing the search in early 2020 when potentially not all publications from 2019 have been indexed in the databases, or an early indicator of a declining interest in the area. There has also been an increased number of publications in 2018 which discussed smart grid and mobile cloud. This could indicate a higher interest in these application areas in the following years. No publications were retrieved from the years before 2010, which coincides with the appearance of the de facto definitions of CPS and cloud computing as terms in [7] and [11], respectively.

The additional coding on document level led to the finding that smart grid was the application area that was mentioned the most frequently, followed by mobile cloud, smart city and cloud manufacturing. This indicates a trend in popular application areas for CCPS architectures for the future.

B. Architectural Viewpoints in CCPS Architecture Discussions

There is a clear preference on the Physical viewpoint for architecture visualizations in CCPS. Functional and Communication viewpoints are the second and third most frequently

Fig. 8. Application areas appearing in publications over time.

chosen viewpoints, respectively. In architecture visualizations which combine multiple viewpoints, the Physical viewpoint is often chosen as a base view, with added information from the Communication, Functional or Implementation viewpoint. Furthermore, many publications depict architectures from more than one viewpoint. This indicates a need to use information from multiple viewpoints in order to describe the system architecture. At the same time, only one of the publications provided information from all six viewpoints.

Additional research needs to be done in order to determine if this effect occurs due to space limitations in scientific publications or if it indicates a lack of comprehensive CCPS architecture descriptions. A more detailed review of selected CCPS architectures may deliver more insights into this matter. Another aspect for further investigation is how in depth descriptions of CCPS architectures are done in the industry. In particular case studies with developed CCPS architectures currently running in production could provide insights into best practices for CCPS architecture development.

C. Cloud Computing in CCPS Architectures

The very low number of publications that cite the NIST definition, as well as the relatively low number of publications which discuss deployment and delivery models indicate a potential misalignment with the common understanding of cloud computing. This could either indicate that cloud computing is regarded as a commodity which does not need further definition or elaboration, or that the term cloud computing is used without providing details on how cloud computing is integrated into the architecture. Regarding the rate in which the cloud providers are mentioned in publications, it seems that most publications do not discuss the usage of existing services from major cloud providers, which is common in publications from the cloud computing domain. In both cases, there is cause for concern with respect to the effective adoption of cloud computing by the research efforts in the CCPS field.

With respect to its usage, cloud computing in CCPS is often associated with big data and data analytics. This relates back to the discussion on the extended storage and computing power of cloud services vs. embedded devices. The frequent mentioning of edge and fog computing is probably related to efforts to bridge the gap between cloud services and embedded devices as well as to the architectural decisions necessary to divide functionality between embedded, fog/edge devices and cloud services.

Future research should investigate further the adoption of cloud services from major providers into CCPS architectures in the industry as well as the academic research community. Another interesting opportunity for future research is to examine research specifically on edge/fog computing and determine how many works talk about CCPS utilizing fog or edge computing without using the term cyber-physical system to describe the discussed systems.

D. Threats to Validity

This section discusses the threats to validity identified in this study, as well as measures taken to mitigate those threats. The discussion follows the schema proposed by Ampatzoglou et al. [16].

Study Selection Validity: The publications included into this study were retrieved via a database search in five different online databases with cyber physical system and cloud computing as population and architecture as intervention. These search terms do not include publications which discuss CCPS architectures without identifying themselves as cyber-physical systems. Different terms for CCPS are present, since such systems are developed in many different application areas and terms like smart grid, mobile cloud, smart city or cloud manufacturing may be used as more narrow terms to refer to application specific CCPS. However, it is not possible to achieve a full coverage of the literature and the amount of included publications from different application areas still indicates a good sample of publications.

Data Validity: As discussed in Section III the majority of extracted data items were retrieved via automated coding to avoid bias in the data extraction step of the process. As the architectural viewpoints had to be extracted manually, the data extraction for this data item was done by both authors independently. Conflicts in the assignment of viewpoints were resolved by discussion between both authors to find a consensus. The application areas extracted as phrases from cloud paragraphs shown in Fig. 7 depicted cloud manufacturing and mobile cloud as most prevalent application areas. However, since the focus of the extraction was on paragraphs that contain the word cloud, those two application areas recieved a disproportional representation. Since both application areas contain the word cloud every paragraph containing the terms was included in the analysis. To mitigate this effect, an additional coding was done on document level to receive the distribution of the extracted application areas in publications over the years.

Research Validity: This study was conducted following the protocol discussed in Section III which follows the guidelines proposed in [6]. To enable repeatability of the study, the data for the taken steps is available in a git repository as discussed in Section III.

VI. Conclusion

This study collected publications on Cloud enabled Cyber Physical (CCPS) architectures and identified an increase in the number of publications in the recent years, in particular in the amount of journal publications showing a maturing field. Most of the collected venues only feature one or two publications on the topic, while IEEE Access is the most popular venue featuring 21 publications on CCPS architecture. Smart grid was determined to be the most frequently mentioned application area, followed by mobile cloud, smart city and cloud manufacturing.

A particular architectural viewpoint was found to be very common in the literature. More specifically, the Physical viewpoint appears to form the foundation for CCPS architecture descriptions. Communication, Functional and Implementation viewpoints are often added to architecture visualizations depicting the Physical viewpoint on a system. Many publications also depict information about CCPS architectures from multiple viewpoints. This indicates that a concise and detailed architecture description requires the information about the system to be depicted from different viewpoints. An opportunity for future research in this direction lays in in-depth evaluations of CCPS architectures in research and industry to determine best practices for detailed CCPS architecture descriptions.

The limited number of publications discussing the standard cloud service delivery and deployment models indicate a potential misalignment with the de facto standard definition of cloud computing from the NIST, or at least an underutilization of cloud computing as a paradigm. Major cloud providers are also not mentioned frequently, which indicates a low degree of attention to existing cloud service offerings within research publications. The frequent usage of the terms edge/fog and IoT indicate a strong relevance of these concepts for CCPS architecture research. Future research should investigate the usage of offerings from major cloud providers in CCPS architectures. Another possible focus area are CCPS architectures which incorporate fog or edge computing.

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