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Edge Computing and Analytics: An Extended Systematic Mapping Study

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***Abstract*— Connected sensors and devices, the Internet of Things, already today produce more data than data connectivity and cloud services can handle. This gives rise to various forms of distributed sensor data handling, from surveillance cameras with built-in feature detection to alarm functionality in temperature sensors. There is an increased interest in being able to use this sensor data for distributed intelligence. The term "Edge Computing" is often used to denote this distributed computing, performed close to the sensors providing the data. Edge Computing enables services typically provided by cloud services with less communication, lower latency, and independence of the internet infrastructure. In this paper, we present a comprehensive, unbiased overview of state-of-the-art research on edge computing and analytics. From the taxonomy of the 90 identified articles, most articles address task scheduling and operation partitioning while data management and engineering, image and facial recognition, power optimization, and anomaly detection are generally also covered. Simulation remains the most used approach for validation, and research results based on implementations of edge systems in real-life environments are still sparse.**

Index Terms*— *edge computing*; *systematic mapping study*; *taxonomy

I. Introduction

In this paper, we discuss the new trends in terms of scientific publications related to edge computing and analytics. We present the protocol of the Systematic Mapping Study (SMS) that we use to select the scientific publications. This article is an extension of a previous SMS we conducted on the same topic [1], which was published at the Cloud Computing 2020 conference. This paper contains all the new publications that have resulted after proceeding with the SMS methodology in continuation to the previous results from April 10^{th} 2019, up to August 25^{th} 2021.

The number of Internet-connected devices, Internet of Things (IoT), was in the year 2018 estimated to be 23 billion and is estimated to grow to 75 billion by year 2025 [2]. The amount of data transferred over the internet is measured in tens of zettabytes per year [3]. Most of the data on the internet is from people sharing and consuming videos, pictures, and sound, but a substantial and growing part is today's data from sensors. There are estimates that in the future, 75 % [4] of the data generated from sensors will be handled close to the sensors. The concept of handling data close to the sensor is often called Edge Computing.

Edge Computing as a term has been used since 2015 [5], solving the issues with providing the emerging amount of data to end-users by content distribution systems and content caches [6]. Today, Edge Computing commonly symbols the distributed computing performed on sensor data, refining the value and usability of the data. This is also driven by the need for distributed intelligence, where subsystems directly or intermittently connected to the Internet should provide autonomous and independent operations. Edge Computing is also driven by the need for low latency [7] and reduced communication costs [8]. Typical use cases for edge computing varies depending on the domain in where is implemented. For industrial implementations, the objective for edge computing is often reduced maintenance costs, optimized operation performance, predictive maintenance, quality improvement, and safety [9].

Edge computing is a technology that can be applied to numerous different areas and domains. It is possible to also learn between domains, where edge computing architectures, equipment, or infrastructures have been successfully deployed and provided value to the operator. The goal of this paper is to find the state-of-art of experimentation, research, and scientific contributions when it comes to edge computing and related technologies.

Our main contributions are as follows:

- We study in which application domains edge computing is applied. Our results indicate that smart cities and homes are the most common targets for edge computing.
- We identify that algorithms doing task scheduling and operation partitioning are the most common algorithms in edge computing.
- Most of the primary studies contribute to architectural edge computing approaches.
- The most commonly used metric for evaluating edge computing systems in the primary studies is the energy efficiency of the proposals.

The remainder of the paper is organized as follows. Section II describes the protocol used for the SMS used to find and evaluate papers in this study. Section III presents the results of the study according to the research questions from Section II-A. In Section IV we discuss the threats related to the validity of the study. Section V summarizes our work.

II. The Systematic Mapping Study

This section describes the protocol used for the Systematic Mapping Study. The protocol is largely based on the one used in [10], but it has been modified according to the topic of this paper.

A SMS is "a broad review of primary studies in a specific topic area that aims to identify what evidence is available on the topic." [11]. The SMS follows a set of guidelines for articles to include in the primary studies: search for articles, remove duplicates, go through screening phases, perform a study quality assessment checklist and procedure. After the screening phase, researchers extract the most important data from papers for performing the data synthesis.

Subsections II-D – II-G describe how the screening phases and the data extraction and synthesis were performed. Since this paper is a continuation on [1], here we only describe how we worked in this extended version.

A. Research Questions

The research questions (RQ) are as follows:

RQ1: In which fields are edge computing applied?
RQ2: What methods or algorithms are used in edge computing?
RQ3: What proposals exist regarding edge frameworks?
RQ4: What kind of performances do proposed solutions have?
RQ5: What is the standardization level on edge computing?
RQ6: How are the proposals evaluated?

B. Search Strategy for Primary Studies

This section presents our search strategy. It is based on the Systematic Literature Review guidelines from [11] [12].

1) Search Terms: Table I lists the search terms used when searching for original papers for this study. The search terms are derived from the research questions.

TABLE I
Search terms with alternate spellings

Term	Alternate Spelling
Edge	
Comput*	Computing, Compute, Computation
Algorithm*	Algorithms
Analy*	Analytic, Analytics, Analytical, Analysis
Algorithm*	Algorithms
Defect*	Defects
Malfunction	
Anomal*	Anomaly, Anomalies
Performance*	Performances
Complexit*	Complexity, Complexities
Energy	

TABLE II
Search strings

#	Search String
1.	Edge AND (Comput* OR Algorithm OR Analy* OR Defect OR Malfunction OR Anomal*) AND (Performance* OR Complexit* OR Energy)
2.	Edge AND (Comput* OR Algorithm OR Analy*) AND (Defect OR Malfunction OR Anomal*) AND (Performance* OR Complexit* OR Energy)
3.	Edge AND (Comput OR Algorithm OR Analy) AND (Defect OR Malfunction OR Anomal) AND (Performance OR Complexit)

2) Search Strings: The search terms listed in Table I were combined into two search strings for use in the digital libraries. These are shown in Table II.

3) Databases: The search strings shown above was applied in the following digital libraries:

- Institute of Electrical and Electronics Engineers (IEEE) Xplore
- Association for Computing Machinery (ACM) Digital library
- ScienceDirect

The first search string was mainly used for the three databases. For the IEEE Xplore database, we used the second search string when searching in abstracts. This was done to reduce the number of papers found because the first search string resulted in more than 32.000 papers in the abstract search. The third search string was used for the Science Direct database because the maximum number of search strings is limited to 8, and asterisks can not be used. We decided to skip the last search term from the original search string. From the collected results from all databases, duplicates were removed.

C. Study Inclusion Criteria

The inclusion criteria for primary studies were as follows:

- Written in English *AND*
- Published in a peer-reviewed journal, conference, or workshop of computer science, computer engineering, embedded systems, signal processing, or software engineering *AND*
- Describing any of the following:
  - Methods or approaches for edge computing or analytics *OR*
  - Infrastructural or architectural approaches to edge computing and analytics *OR*
  - Performance evaluations of existing edge computing and analytics approaches

If several papers presented the same approach, only the most recent was included, unless the contributions of those papers were different.

D. Title and Abstract Level Screening

In this phase, the inclusion criteria in Section II-C were applied to publication titles and abstracts. One researcher first screened all the titles from the databases. Consequently, two researchers independently screened the abstracts, excluding all papers that were not relevant for this study. When a researcher was uncertain about including or excluding a particular paper, he discussed it with the other researchers to decision. The results from this phase were used as starting point for the full text screening.

E. Full Text Level Screening

In this phase, the remaining papers were analyzed based on their full text. Four researchers applied the inclusion criteria in Section II-C on the full text. Here, each of the four researchers screened a quarter of the total number of articles. The researchers also documented a reason for each excluded study [13].

F. Study Quality Assessment Checklist and Procedure

The selected papers were assessed based on their quality. Four researchers assessed the quality of the selected papers, each one assessing a quarter of the total number of papers. Any papers not meeting the minimum quality requirements were excluded from the set of primary studies. The output from this phase was the final set of papers listed in Table VI.

Table III presents the checklist for the study quality assessment. For each question in the checklist, a three-level numeric scale was used [13]. The levels were: yes (2 points), partial (1 point), and no (0 points). Based on the checklist and the numeric scale, each study could score a maximum of 34 and a minimum of 0 points. We used the first quartile $(34/4 = 8.5)$ as the cutoff point for the inclusion of studies. Therefore, if a study scored 8 points or less, it was excluded due to its lack of quality with respect to this study. The researcher documented the obtained score of each included/excluded study.

TABLE III
STUDY QUALITY ASSESSMENT CHECKLIST, PARTIALLY ADOPTED FROM [10], [13]

#	Question
Theoretical contribution	
1	Is at least one of the research questions addressed?
2	Was the study designed to address some of the research questions?
3	Is a problem description for the research explicitly provided?
4	Is the problem description for the research supported by references to other work?
5	Are the contributions of the research clearly described?
6	Are the assumptions, if any, clearly stated?
7	Is there sufficient evidence to support the claims of the research?
Experimental evaluation	
8	Is the research design, or the way the research was organized, clearly described?
9	Is a prototype, simulation, or empirical study presented?
10	Is the experimental setup clearly described?
11	Are results from multiple different experiments included?
12	Are results from multiple runs of each experiment included?
13	Are the experimental results compared with other approaches?
14	Are negative results, if any, presented?
15	Is the statistical significance of the results assessed?
16	Are the limitations clearly stated?
17	Are the links between data, interpretation and conclusions clear?

G. Data Extraction Strategy

We used the form shown in Table IV to extract data from the primary studies. Four researchers extracted the information from the papers, and each researcher obtained data from one-quarter of the papers. The extracted data was then used for analysis. We extracted such data that it could be used for answering the research questions listed in Section II-A.

TABLE IV
DATA EXTRACTION FORM

Data Item	Value	Notes
General		
Data extractor name		
Data extraction date		
Study identifier (S1, S2, S3, ...)		
Bibliographic reference (title, authors, year, journal/conference/workshop name)		
Publication type (journal, conference, or workshop)		
Edge Computing and Analytics Related		
(RQ1) The domain in which the edge analytics are applied (e.g., smart cities, industry, air industry, shipping, heavy/professional vehicles, health sector)		
(RQ2) Edge computing and analytics method or algorithm		
(RQ3) Edge framework (infrastructure or architecture)		
(RQ4) Performance metrics of proposal (e.g., algorithm complexity, computing, data compression, energy requirements, real-time)		
(RQ5) Mentions of standardization level		
(RQ6) Evaluation method (analytical, empirical, simulation)		

H. Synthesis of the Extracted Data

The extracted data from the papers was used for analysis in order to obtain a high-level view of different aspects related to edge analytics. The papers were categorized in different ways, and collective results were extracted. The results from this phase are presented and discussed in Section III.

III. RESULTS

In this section, we present the main findings of the research. We did the first paper search on April 10^{th} 2019, and the results from that search are reported in [1]. On August 25^{th} 2021, we performed the second paper search. The results presented in this section summarise both of the searches performed.

Several contexts of research contain search terms such as ”edge” and ”algorithm.” Out of the results gathered, some findings did not relate to edge computing. They focused on other examples, such as analysis of image edges or parsing methods for graph edges.

Table V shows the number of papers at the end of each phase of the study. As can be seen, the initial paper search resulted in a large number of papers. From the initial number of papers found using the search strings mentioned in Section

II-B2, we decided to discard papers from earlier than 2016. The discarding of papers was done after the title and abstract screening. To our understanding, the term "edge computing" was introduced at the end of 2015 [5]. In addition, we also discarded papers related to mobile edge computing, as our research relates to the industrial environment. On the other hand, papers related to fog computing were not discarded, because the technologies used in fog computing are closely related to edge computing.

TABLE V
THE NUMBER OF PAPERS IN EACH PHASE OF THE PROTOCOL

Phase	Number of papers
Initial search results without duplicates	3524
After title and abstract screening	236
After full text screening	123
After quality assessment	90

The initial paper search from the previous study and the search performed in this study resulted in 3524 papers after removing all duplicates. After the title and abstract screening, only 236 papers were included for the next screening phase. Less than half of these papers were included after the full text screening, resulting in 123 papers for the quality assessment. In the quality assessment phase, a few papers were excluded. The number of primary studies included in this research is 90. Of the 90 primary studies, 51 have been published in conference proceedings. The remaining 39 papers have been published in journals.

The term "edge computing" was firstly mentioned by the ending of 2015, according to a publication of Garcia Lopez et al. [5]. Figure 1 illustrates the publication years of the primary studies. During 2018 many publications related to edge computing appeared. During the following years, there has been a noticeable decrease in the number of publications.

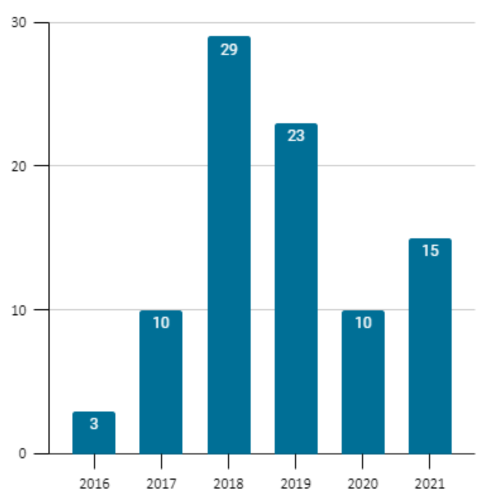

Fig. 1. Reviewed articles sorted by publication years

TABLE VI
PRIMARY STUDIES INCLUDED, WITH CORRESPONDING REFERENCES

ID	Reference	ID	Reference	ID	Reference
S1	[14]	S31	[15]	S61	[16]
S2	[17]	S32	[18]	S62	[19]
S3	[20]	S33	[21]	S63	[22]
S4	[23]	S34	[24]	S64	[25]
S5	[26]	S35	[27]	S65	[28]
S6	[29]	S36	[30]	S66	[31]
S7	[32]	S37	[33]	S67	[34]
S8	[35]	S38	[36]	S68	[37]
S9	[38]	S39	[39]	S69	[40]
S10	[41]	S40	[42]	S70	[43]
S11	[44]	S41	[45]	S71	[46]
S12	[47]	S42	[48]	S72	[49]
S13	[50]	S43	[51]	S73	[52]
S14	[53]	S44	[54]	S74	[55]
S15	[56]	S45	[57]	S75	[58]
S16	[59]	S46	[60]	S76	[61]
S17	[62]	S47	[63]	S77	[64]
S18	[65]	S48	[66]	S78	[67]
S19	[68]	S49	[69]	S79	[70]
S20	[71]	S50	[72]	S80	[73]
S21	[74]	S51	[75]	S81	[76]
S22	[77]	S52	[78]	S82	[79]
S23	[80]	S53	[81]	S83	[82]
S24	[83]	S54	[84]	S84	[85]
S25	[86]	S55	[87]	S85	[88]
S26	[89]	S56	[90]	S86	[91]
S27	[92]	S57	[93]	S87	[94]
S28	[95]	S58	[96]	S88	[97]
S29	[98]	S59	[99]	S89	[100]
S30	[101]	S60	[102]	S90	[103]

A. Application Domains of Edge Computing (RQ1)

Research question 1 strives to identify the domain in which edge computing has been applied in the primary studies. Figure 2 illustrates those domains. Smart cities and homes are the dominating domain of application in the primary studies, and professional vehicles, the health sector, and the industry have also been the application domain in other primary studies. We also included a category named "Other." This category covers more domain-specific applications such as tracking systems for drinking activity, micro-services, social media applications, or data centers.

In the majority of the primary studies, however, the domain of application was not specified. Consequently, those papers provided more general contributions that possibly could be applied in several different fields.

B. Edge Computing Method or Algorithm (RQ2)

Table VII shows the purpose of algorithms used in the primary studies.

Approximately one-third of the primary studies relied on algorithms used for task scheduling and operation partitioning, which is understandable since those characteristics are essential when implementing edge systems. One of the second most addressed uses for algorithms was addressing power optimization. It is understandable since often edge computing is applied to small devices with limited resources, most notably computing power and battery. Therefore, power optimization

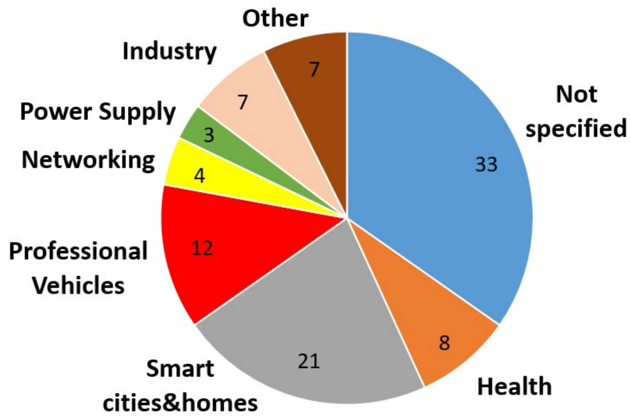

Fig. 2. Edge computing application domains from reviewed studies

is a necessary factor to consider in edge computing. Many primary studies contributed with algorithms related to image and video processing, data transmission, reduction, and mining. A smaller number of primary studies contributed with algorithms related to anomaly detection, audio measurements, or time efficiency. When comparing Table VII with the results we presented in our previous work [1], it is evident that there has been a noticeable increase in publications that contribute with algorithms.

C. Edge Computing Framework (RQ3)

Figure 3 shows the number of papers that contributed to architectures or infrastructures. In some study identifiers, the design was presented as a framework, while others proposed a method. However, the proposals were widely varying, and we were unable to classify the frameworks any further. This research question was consequently challenging to answer. Also, the distinction between architecture and infrastructure may be vague, considering that the infrastructure describes the set of components that make up a system whereas, the architecture represents the design of those components and their relationship. In our rough classification, we considered architecture mostly device-internal and infrastructure on an edge device network level.

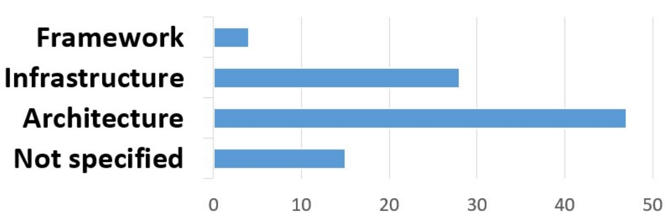

Fig. 3. Articles organized by the type of edge framework proposed

D. Performance of the Proposals (RQ4)

The purpose of RQ4 was to evaluate the performances of the edge systems presented in the primary studies. As can be seen in Table VIII, 40 primary studies provided energy-efficient solutions by reducing the energy requirements for performing tasks. Real-time solutions exist in 23 of the primary studies. With real-time, we mean that results were available with minimal but approximately constant delay, and the papers included in this category were such that it was evident that they were real-time solutions. Some 33 primary studies focused on the improvement computational efficiency of the system by reducing the time required to complete specific tasks and reducing the overall memory usage. In addition, nine primary studies focused on network performance issues. Nine primary studies could not fit into the above classes. These primary studies were on task scheduling, road anomaly detection, and superiority in lane switching scenarios.

E. Edge Analytic Standardization Level (RQ5)

In this research, we analyzed the level of standardization used in edge computing and references to ongoing standardization initiatives for edge computing systems. In our previous study, no publication relied on any edge computing-related standard. The situation is still the same based on our extended search. A few primary studies used standards such as Controller Area Network (CAN), IEEE P1363, and NGSI when implementing edge computing, but these are not strictly edge-related. Corresponding references were made to communication standards such as IEEE 802.11, Wi-Fi, and video codecs MPEG and H.264/H.265 (HEVC) used in edge system implementations. Considering that edge computing standards were not used in the research, a reference to edge level standardization existed that was at the time ongoing within ETSI [104]. It was published in 2017 by ETSI Industry Specification Group with the title: "Mobile Edge Computing (MEC) - Mobile Edge Platform Application Enablement." Another potential reference that may support the implementation of edge systems in the future was the preparatory work of ISO/IEC JTC 1/SC 41. This Subcommittee 41 is currently preparing standards on the area of the Internet of things and digital twins [105].

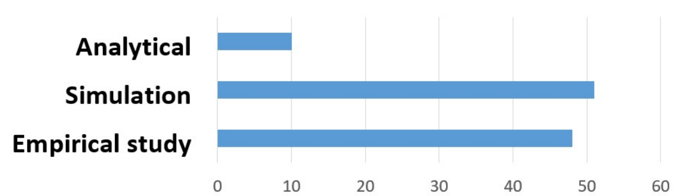

Fig. 4. Evaluation methods

F. Proposal Evaluation Methods (RQ6)

The evaluation of the proposed approach is an essential part of research and scientific papers. The performance and effectiveness of the contribution can be assessed when evaluating the proposal concerning the requirements. The same applies when compared to other approaches. In this study, we analyzed the evaluation methods that were used in the primary studies. Figure 4 illustrates that approaches evaluations were

TABLE VII
TARGETS FOR USING ALGORITHMS IN THE PRIMARY STUDIES

Algorithm Output	Count	Primary Studies	Description
Task Scheduling & Operation Partitioning	29	S7, S11, S13, S16, S20, S23, S26, S27, S31, S34, S40-S42, S44, S45, S47, S50, S57, S68, S69, S70-S72, S74-S77, S80, S81	Decision trees, appliance scheduling, routine handler, offloading algorithm, Markov decision process, sorting, readjustment algorithm
Data Transmission/Reduction/Mining	15	S1, S4, S24, S32, S49, S51, S52, S55, S56, S62, S63, S66, S75, S85, S89	Used for data management
Power optimization	15	S2, S5, S6, S8, S18, S19, S21, S22, S26, S27, S35, S79, S82, S84, S86	Power consumption reduction
Image Classification & Face Recognition & Video Processing & Pattern Recognition	15	S10, S17, S28, S29, S30, S48, S52, S58, S60, S61, S73, S77, S78, S82, S84	Image/video classification recognition, accuracy measurement, fuzzy classification, signal processing in healthcare, lane switching guidance, route planning of autonomous flight devices
Anomaly Detection	12	S12, S15, S37, S53, S54, S64, S80, S83, S87, S88, S89, S90	Vehicle anomaly detection, control loops, digital twin, anomalies in health edge systems, detection of malicious data from edge devices, classifier for predicting component failures
Audio Measurements & Time efficiency & Localization	4	S35, S39, S43, S52	Mosquito wing-beats classification, Bluetooth low energy localization, delay reduction

TABLE VIII
PERFORMANCE METRICS IN THE PRIMARY STUDIES

Performance Metric	Count	Primary Studies	Description
Energy Efficiency	40	S3-S6, S8-S11, S14, S15, S16, S18-S23, S26, S27, S29, S31, S32, S34, S35, S38, S43, S44, S45, S47, S49, S50, S52, S57, S58, S60, S70, S82, S85, S86, S89	Reduced energy requirements for performing computations; power savings; increased battery life of wearable health monitoring devices; early notification from critical health condition
Computational Efficiency	33	S2, S7, S33, S37, S39, S41, S51, S53, S54, S56, S61-S69, S74-S78, S80, S81, S83-S88, S90	Reduced computation time and memory usage; detection of road anomalies; anomaly detection; tracking precision; improved system utility; reduction of operating flight costs; classifiers comparison
Real-time	23	S1, S12, S13, S24, S28, S29, S30, S34, S35, S36, S39, S40, S43, S45, S46, S48, S55, S63, S72, S73, S77, S78, S80	Real-time computation; minimal delay; delay patterns in communication technology; water surface profile predictions; driver notification of critical events
Network performance	9	S17, S25, S30, S36, S45, S59, S71, S76, S79	Network architectures for data transmission; enhancing data availability; efficient bandwidth usage
Other	9	S27, S28, S34, S40, S42, S51, S58, S57, S85	Task scheduling; road anomalies detection; superiority in lane switching scenarios

achieved using analytical, simulation, or empirical studies. In most of the primary studies, simulations were used for evaluation. However, empirical studies were used in almost as many cases. The earlier study shows that there is an increase in the share of empirical evaluations about simulations. Different evaluation methods combinations were used in several studies. In 15 primary studies, empirical evaluation was supported by simulation. In four primary studies, simulation was used along with analytical evaluation. Among the primary studies that were evaluated by empirical studies, case studies were the dominant method chosen. Even though the case studies relied on real-implementations for the evaluations, they used a lab environment for experiments. It means that the conditions for assessment were constructed and controlled by the researchers. In lab test circumstances, there are typically some differences when compared to the actual operating environment. Due to this, some case-specific events that might take place in natural environments may not be admitted in the evaluation phase.

IV. THREATS TO VALIDITY

A threat to the validity of this study is that we dismissed papers related to mobile edge computing since this study focused on edge computing and analytics in non-mobile environments. Consequently, the authors may not have added some relevant papers to this study.

This study also only included papers published from 2016 onward. The reason was that the appearance of the term ”edge” came towards the end of 2015. This way, there may be papers published related to this paper’s topic that was published earlier and subsequently missed.

Another threat to validity is that the screening phases were performed partially by different persons. No researcher followed the entire protocol from beginning to end, but instead, the screening work was divided between the researchers due to time constraints. The researchers may have had different views regarding paper relevancy, potentially excluding relevant papers.

The work-related data extraction was divided between the researchers. The data extracted in our previous work [1] was double-checked by other researchers, but due to time constraints, we were not able to double-check the data extracted in this extended work. The authors may have missed some of the data during the data extraction phase.

We point out, however, that in our previous work [1], we had consensus discussions in every phase of the protocol. In this extended work, whenever a researcher was uncertain whether to include or exclude a paper, he discussed the matter with the other researchers. Therefore, we believe that the risk of researchers having made mistakes while following the protocol is small.

V. Conclusions

In this paper, we presented a systematic mapping study on edge computing and analytics. The term ”edge computing” is moderately new, but it is the same category as other terms such as Internet of Things or fog computing. The term shifts nowadays towards being included in a more widespread section of ”distributed intelligence.”

We have found an increased number of papers that focused on the application domain of smart homes and cities, professional vehicles, industry, and health. However, among the primary studies we selected, power supply and networking had lower application domains, indicating a clear gap for those fields.

Most of the primary studies we identified focused on task scheduling and operation partitioning. Data management and engineering, image and facial recognition, power optimization, and anomaly detection are other targets for using algorithms within the primary studies. Similar to the previous article, the simulation remains widely used as a tool for validation. The implementation of edge systems is still somewhat sporadic with a few real-life experiments.

Many of the primary studies did not specify the application domain. A similar situation is happening within the specification of the edge framework. Those indicate a lack of strategy for implementing the authors’ proposals.

Acknowledgments

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