A Systematic Mapping Study on Edge Computing and Analytics

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***Abstract*—The vast amount of data provided by the Internet of Things and sensors, have given rise to edge computing and analytics. In edge computing and analytics, data processing and analysis on sensor input is performed in edge devices prior to sending the results to the cloud. This reduces required processing in the cloud while minimizing communication network utilization and allows cloud resources to be used for other tasks such as decision making. In this paper, we present a comprehensive, unbiased overview of state-of-the-art research on edge computing and analytics. Of the 47 identified papers, several have targeted task scheduling and power optimisation, while data management and engineering, image and facial recognition as well as anomaly detection were not well studied. Simulation remains the most used approach for validation, and research results based on implementations of edge systems in real life environments are still sparse.**
Keywords-edge; analytics; systematic mapping study.

I. INTRODUCTION

An increasing part of new features and added value for machines and technical solutions comes from digitalization and advanced automation. The Internet of Things, collections of Big Data and cloud-based analytics provide potential tools to improve machine reliability, performance and energy efficiency. However, required network bandwidth, data storage and data processing power (as well as the resulting energy consumption) are significant for machines equipped with large sensor systems. Due to these issues, the implementation of analytics systems for condition monitoring, diagnostics and predictive maintenance would be largely unfeasible if not for edge computing and analytics to perform data collection, storage, computation and analysis closer to original locations. Edge analytics can take place on a sensor or other device connected directly to a machine, instead of transmitting the data to the cloud or central data storage, for example. This approach shortens analytics response times and reduces the bandwidth needed for data transmission.

According to analysis by [1], the business drivers supporting edge application use are low latency, cost efficiency, improved operational efficiency and lower bandwidth. However, implementation of edge-based analytics supporting machine diagnostics remains rare. At the same time, a market review [2] has forecast that revenue from condition monitoring applications, which might utilize edge analytics, will almost triple between 2019 and 2023. As such, edge computing and analytics hold significant interest and potential for both companies and research institutes.

This paper presents an overview of state-of-the-art technologies and solutions used for edge computing and analytics. These paradigms are already applied in many areas, such as mobile devices [3], home automation [4], smart cities [5], personal health care [6], automotive and industrial vehicles [7]. The goal of this study was to reveal existing frameworks, infrastructures, methods and algorithms for edge analytics, including their performances and the level of standardization for edge analytic systems. The study was performed using systematic mapping study (SMS) protocol presented in Section II that covered hundreds of scientific publications from several digital libraries.

This study was performed in the context of a Finnish national research project on edge technologies, which has been carried out in co-operation with several industrial companies. The motivation of companies to apply edge computing to their machines relates to condition monitoring and machines diagnostics. The main application areas for the companies are energy production, mobile work machines and related monitoring and AI solutions. Therefore, scientific papers focusing on mobile edge computing were not included and the focus was on industrially applicable solutions.

The contributions of this paper are to provide such an overview and results from applying SMS methodology to this research area. Given that none of the 912 papers found after the initial search provided a similar overview of edge computing and analytics, we deem the results provided in this paper to be relevant.

The paper is structured as follows. Section 2 describes the protocol for the systematic mapping study used to find and evaluate papers in this study. The protocol is described in detail for the purpose of replicability. In Section 3, we present the results of this study, where we also try to answer the research questions presented in Section 2. Potential threats to the validity of this study are discussed in Section 4, and in Section 5, we present our conclusions.

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II. The Systematic Mapping Study

This section describes the protocol used for the SMS. The protocol is largely based on the one used in [8], but it has been modified according to the topic of this study.

A. Research Questions

The research questions (RQ) are as follows:

RQ1: Which fields apply edge computing?
RQ2: What methods or algorithms are used in edge computing?
RQ3: What edge framework proposals exist?
RQ4: How do proposed edge framework solutions perform?
RQ5: What is the standardization level for edge computing?
RQ6: How are the edge framework proposals evaluated?

B. Search Strategy for Primary Studies

This section presents our search strategy, which based on the systematic literature review guidelines from [9] and [10].

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	
Analy*	Analytic, Analytics, Analytical, Analysis
Algorithm*	Algorithms
IoT	Internet of Things
Complexit*	Complexity, Complexities
Autonomous	
Performance*	Performances
Malfunction	
Defect*	Defects
Anomal*	Anomaly, Anomalies
Machine	
Device	
Comput*	Computing, Compute, Computation
Energy	

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.

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) Databases: The search strings shown above were applied to the following digital libraries:

- IEEE Xplore
- ACM Digital library
- ScienceDirect

We decided to start with four libraries, but skipped the SpringerLink database because it did not have the option of extracting papers in a bibtex file format.

The first search string was used for all three databases while the second string was used to search abstracts in the IEEE Xplore database only. This was done to reduce the number of papers found, because the first search string resulted in more than 11,000 papers from the abstract search.

Since the digital libraries have different possibilities for defining search strings, the strings were customized to every digital library. Duplicates were removed from the collected results.

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 covering the subjects of computer science, computer engineering, embedded systems, signal processing, or software engineering *AND*
- Describing any one of the following:
  - Methods or approaches for edge computing or analytics
  - Infrastructural or architectural approaches to edge computing and analytics
  - 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 differed.

D. Title and Abstract Level Screening

In this phase, the inclusion criteria were applied to publication titles and abstracts. To minimize researcher bias, two researchers independently analysed the search results. Afterwards, the analyses were compared and any disagreements were resolved through discussion. The screening results were used as a starting point for the full text screening.

E. Full Text Level Screening

In this phase, the remaining papers were analysed based on their full text. To minimize bias, three researchers applied the inclusion criteria on the full text. Here, one researcher screened all of the papers, while the remaining two researchers screened half of the papers each, due to time limitations. The results were compared and disagreements were resolved through discussion. The researchers also documented a reason for each excluded study [11].

F. Study Quality Assessment Checklist and Procedure

The selected papers were assessed based on their quality in terms of contribution to edge analytics. Three researchers assessed the quality of the selected papers with one researcher assessing all of the papers independently, while the two other researchers assessed half of the papers each. After the assessing, the results were compared and disagreements were resolved through discussion between researchers. Any papers not meeting minimum quality requirements, as detailed below, were excluded from the set of primary studies. The output from this phase was the final set of papers.

Table III presents the checklist for study quality assessment. For each question in the checklist, a three-level, numeric scale was used [11]. The levels were: yes (2 points), partial (1 point), and no (0 point). Based on the checklist and the numeric scale, each study could score a maximum of 34 and a minimum of 0 points. If a study scored 8 points or less, it was excluded due to a lack of quality with respect to this study. The reviewing researcher documented the obtained score of each included/excluded study.

TABLE III. STUDY QUALITY ASSESSMENT CHECKLIST, PARTIALLY ADOPTED FROM [8][11]

#	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. Three researchers extracted the information from the papers with each researcher extracting data from one third of the papers. After the data extraction, the results were double-checked by the reviewing researchers. The extracted data was then used for analysis, applying RQs from Section II-A to obtain answers.

H. Synthesis of the Extracted Data

The extracted data from the papers was analysed to to obtain a high-level view of the different aspects related to edge analytics. The papers were categorised and collective results were extracted. The results from this phase are presented and discussed in Section III.

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)		

III. RESULTS

In this section, we present the main findings of the research. We used search terms such as ”edge” and ”algorithm*” that are used in several research contexts. Consequently, some findings were not related to edge computing. For example, some papers were related to the analysis of image edges or parsing methods for graph edges, which are not related to the topic of this paper.

As seen in Table V, the initial paper search produced an excessive number of papers. After the initial screening, it turned out that no papers found and published before 2016 were on the topic industrial edge analytics. Therefore, the results of this study include papers published from 2016 onwards. We also discarded papers related to mobile edge computing, as our research relates to the industrial environment. That being said, papers related to fog computing were not discarded, because the technologies used are closely related to edge computing. These are the main reasons to the large number of papers discarded after the title and abstract screening.

TABLE V. NUMBER OF PAPERS IN EACH PHASE OF THE PAPER SEARCH AND SCREENING

Phase	Number of papers
Initial search results without duplicates	912
After title and abstract screening	118
After full text screening	58
After quality assessment	47

After the initial paper search, 912 papers were found after removing all duplicates. After the title and abstract screening, only 118 papers were included in the following phase. After the full text screening, 58 papers were included in the quality assessment.Only a few papers were discarded based on the quality assessment, leaving 47 primary studies for the final analysis. Overall, a significant number of papers were discarded, as their content (e.g., graphs, decision trees) did not relate to the industry domain of edge analytics. Most of the primary studies (38) were published in conference proceedings and the remainder (9) were published in journals.

As shown in Figure 1, the subject of edge computing is trending toward greater interest over time. We note that while there were few papers used from 2019, the initial paper search took place on April 10, 2019. As such, this study most likely does not include all related articles published in 2019.

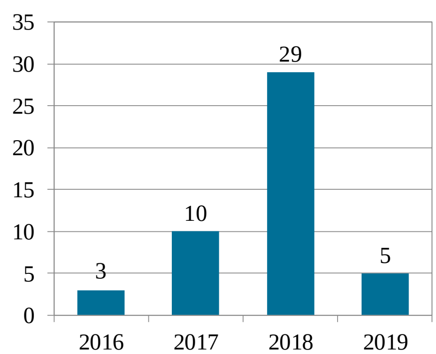

Figure 1. Reviewed papers sorted by publication year

A. Application Domains of Edge Computing (RQ1)

The idea behind RQ1 was to identify domains in which edge computing has been studied, and these domains are illustrated in Figure 2. According to our findings, smart cities and homes were application domain of many primary studies. However, the majority of these studies did not have a specific application domain, providing general contributions that could be applied to several domains.

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 expected, since those characteristics are important when implementing edge systems. The second-most addressed use for algorithms was addressing power optimisation, which is also understandable as task scheduling and operation partitioning are closely related to power consumption. A substantial number of papers contained algorithms related to image and video processing as well as data transmission, reduction, and mining. Only

TABLE VI. PRIMARY STUDIES INCLUDED, WITH CORRESPONDING REFERENCES

ID	Reference	ID	Reference
S1	[12]	S25	[13]
S2	[14]	S26	[15]
S3	[16]	S27	[17]
S4	[18]	S28	[19]
S5	[20]	S29	[21]
S6	[22]	S30	[23]
S7	[5]	S31	[24]
S8	[25]	S32	[26]
S9	[27]	S33	[28]
S10	[29]	S34	[30]
S11	[31]	S35	[32]
S12	[7]	S36	[33]
S13	[34]	S37	[35]
S14	[36]	S38	[37]
S15	[38]	S39	[39]
S16	[4]	S40	[40]
S17	[41]	S41	[3]
S18	[42]	S42	[43]
S19	[44]	S43	[45]
S20	[46]	S44	[47]
S21	[48]	S45	[49]
S22	[50]	S46	[6]
S23	[51]	S47	[52]
S24	[53]		

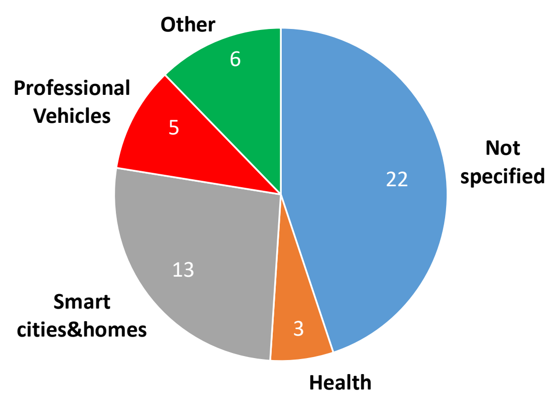

Figure 2. Edge computing application domains from reviewed studies

a few papers used algorithms related to anomaly detection, audio measurements or time efficiency. In general, Table VII shows that the area of edge computing and analytics is quite new, and more research effort is needed especially in the less addressed categories.

C. Edge Computing Framework (RQ3)

Figure 3 shows the number of papers that contributed with architectures or infrastructures. However, proposals varied widely and could not be classified further and the distinction between the two terms may be considered vague. This research question was consequently quite difficult to answer. Nonetheless, in our classification, we considered architecture to be device-internal mostly and infrastructure to be an edge-device network.

TABLE VII. TARGETS FOR USING ALGORITHMS IN THE PRIMARY STUDIES

Algorithm Output	Count	Primary Studies	Description
Data Transmission/Reduction/Mining	4	S1, S4, S24, S32	Data management and engineering
Power optimisation	9	S5, S6, S8, S18, S19,S21,S26, S27, S35	Power consumption reduction, anomaly detection
Task Scheduling & Operation Partitioning	16	S7, S11, S13, S16, S20, S23, S26, S27, S31, S34, S40, S41, S42, S44, S45, S47	Decision trees, appliance scheduling, routine handler, offloading algorithm
Anomaly Detection	3	S12, S13, S37	Vehicle anomaly detection, control loops, anomaly detection
Image Classification & Face Recognition & Video Processing & Pattern Recognition	4	S10, S17, S28, S29, S30	Image classification, face recognition, Markov model, image recognition, video processing
Audio Measurements & Time efficiency & Localization	3	S35, S39, S43	Mosquito wing-beats classification, BLE localization, delay reduction

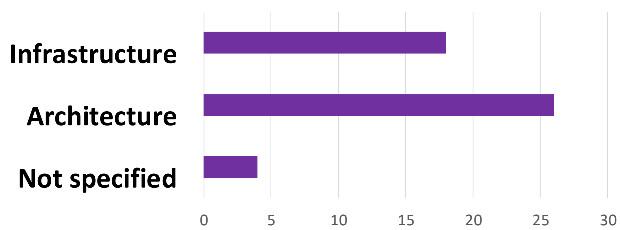

Figure 3. Articles organized by the type of edge framework proposed

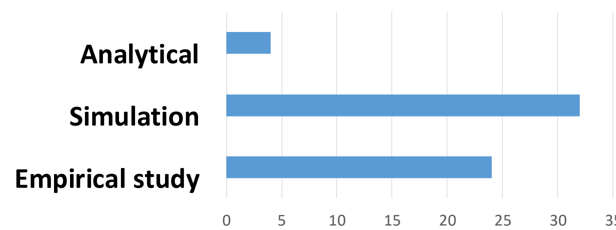

Figure 4. Evaluation methods

D. Proposals Performance

(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, 29 primary studies provided energy efficient solutions, mostly by reducing energy requirements for performing tasks. Solutions working in real-time i.e., providing results with minimal but approximately constant delay) were provided by 15 of the primary studies. Five primary studies provided solutions that improved computational efficiency by reducing the time required to complete certain tasks and reducing overall memory usage. Only two primary studies addressed data transmission in edge systems. The remaining nine primary studies measured various phenomena that was not easily categorised.

E. Edge Analytics Standardization Level (RQ5)

In this research, we analysed what level of standardization has been used in edge computing. According to our findings, no primary study mentioned relying on any edge computing-related standard. A few primary studies used standards that are not strictly edge-related (e.g., Controller Area Network, IEEE P1363 and NGSI), but standardization is ongoing for multi-access edge computing within European standards telecommunications institute [3].

F. Proposal Evaluation Methods (RQ6)

Evaluating proposed approaches is an important part of the this study, allowing the effectiveness if each contribution to be acknowledged and compared to other approaches. We analysed the evaluation methods that were used in the primary studies by using analytical, simulation and empirical studies (Figure 4). In the majority of the primary studies, the evaluation was conducted by performing simulations. However, empirical studies were also used in many studies. We point out that in some papers, a combination of these evaluation methods were used. 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 their evaluations, they were mostly applied in lab environments, meaning that the evaluations were controlled by the researchers. Such environments tend to prevent events that occur in real environments.

IV. THREATS TO VALIDITY

A threat to validity of this study is that papers related to mobile edge computing were not included, since this study focused on edge computing and analytics in non-mobile environments. Consequently, some relevant papers may have been missed.

This study also only included papers published from 2016 onward, largely due to the appearance of the term ”edge” towards the end of 2015. As such, there may be papers published related to this paper’s topic that were published earlier and subsequently missed. There may, however, exist papers published earlier that are related to the topic of this paper, and if that is the case, those papers have been missed.

Another threat to validity is that the screening phases were performed partially by different persons. While one researcher followed the entire protocol from beginning to end, the remaining researchers had varying influence on the screening phases. These researchers may have had different

TABLE VIII. PERFORMANCE METRICS IN THE PRIMARY STUDIES

Performance Metric	Count	Primary Studies	Description
Real-time	15	S1, S12, S13, S24, S28, S29, S30, S34, S35, S36, S39, S40, S43, S45, S46	Computations are performed while the system is running. Results are available with minimal delay.
Computational Efficiency	5	S2, S33, S37, S39, S41	Reduced computation time and memory due to the use of edge system.
Energy Efficiency	29	S3, S4, S5, S6, S8, S9, S10, S11, S14, S15, S16, S18, S19, S20, S21, S22, S23, S26, S27, S29, S31, S32, S34, S35, S38, S43, S44, S45, S47	Reduced energy requirements for performing computations due to the use of edge system.
Data Transmission	2	S25, S45	Reduced response times, improved transmission rates
Other	9	S7, S17, S27, S28, S30, S34, S36, S40, S42	Task scheduling, latency, network performance, flexibility, quality of service, system bandwith, runtime performance

views regarding paper relevancy, causing relevant papers to be excluded.

In all phases where three researchers were involved, except for the data extraction phase, one researcher completed the entire phase independently, while the other two divided the workload evenly between them. Since the workload was divided, some papers may have been excluded because of differing criteria for relevance.

In the data extraction phase, each of the researchers extracted data from one third of the papers. Although each set of extracted data was double-checked by other researches in the group, there is a risk that some data may have been missed.

Finally, we point out that after each phase in the protocol, consensus discussions were held and any disagreements were resolved. Therefore, we feel any threats posed to protocol execution were minimal.

V. CONCLUSIONS

We have presented a systematic mapping study on edge computing and analytics. For the purpose of replicability, the protocol used in the study was also presented. Since the term ”edge” is rather new, the papers we identified were all published in 2016 or later.

In our findings, several papers targeting task scheduling and power optimisation while few addressed other targets (such as image and face recognition, anomaly detection, data management and data engineering) to indicate a clear information gap for those fields. Many papers relied on simulating their proposals and few offered real implementations of edge technologies. Many situations, however, are difficult to simulate, because of events that are either unknown, rare or hard to predict.

Almost half of the papers did not specify their application domain, indicating that clear implementation strategies for some proposals did not exist. Among the application domains specified, smart cities and homes were the dominating application hldomains, followed by professional vehicles, the health domain, and various other domains.

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