A Tertiary Study on Open Source Software Research

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ABSTRACT

Context: Open-source software (OSS) development has gained popularity in the last two decades, having major research in OSS evolution, adoption, and development. Multiple Systematic Literature Reviews (SLR) and Systematic Mapping Studies (SMS) are published in the OSS domain; however, many areas are still open for research.
Objective: The study aims to aggregate and classify OSS research areas, topics, and, future directions.
Method: A systematic tertiary study is performed to cover all the systematic secondary studies in the area of OSS. The guidelines of Kitchenham are used for designing the protocol.
Result: We identified seventy-four studies that consist of twenty-five SMS and forty-nine SLR. The literature is mapped to a published taxonomy of OSS by Aksulu and Wade, however, the future directions are thematically analyzed. The results of mapping show that the highest number of studies (forty-seven) are in the sub-category of "*OSS categorization/research agenda*". Eight studies are mapped to the sub-category "*OSS vs Proprietary*". These studies fall in the main category of "*Conceptual*". The second major work is in the "*OSS Production*" main category in the sub-categories of "*Communities*" (ten), "*Process*" (eight), "*User and Developer Motivation*" (nine), and "*Self-Organization (Product and Community Evolution)*" (six). Seven studies are also mapped to the sub-category of "*Software Quality*" in the main category of "*Performance Metrics*". Other categories have fewer studies mapped to them. The areas identified, thematically, for future directions are "OSS contributors", "OSS development process", "OSS evolution and prediction", "use of OSS in different domains", and "OSS adoption/adaptation/integration".
Conclusion: The mapping between "key research areas" of systematic secondary studies and "taxonomy categories" shows that there is no or little research in some of the categories of taxonomy, having potential of future research. The future direction thematic analysis will also aid researchers and practitioners.

INDEX TERMS Tertiary Study , Open-Source Software (OSS), Systematic Literature Review (SLR), Thematic Analysis , Open-Source Research (OSR)

I. INTRODUCTION

Open-Source Software (OSS) has surfaced as an innovative way of developing, acquiring, distributing, redistributing, and using software [14, 17]. OSS development has emerged as a different strategy from traditional development, as it is collaborative and voluntary development performed by geographically dispersed developers [17]. The volunteers are free to choose what they want to do, when, and on which project without following any plan, design, or even a delivery timeline [17]. OSS projects depend on the health and strength of the developing community [30]. Commercial firms are also responsible for setting up and participating in the OSS communities [14]. There are many benefits of using OSS such as reduced cost, reduced development time, less time to market, increased innovation, business competition, good quality, security, and customization [33, 27, 16]. OSS also has some challenges and risks associated with it [14] for example, the challenge of knowledge management in OSS due to the distributed nature of the project [7], attraction and sustainability of newcomers [34], creating and maintaining a community around technology and other hidden costs [11]. The benefits of OSS can only be achieved by carefully addressing the challenges and risks associated with the selection, development, customization, and use of the OSS [14]. The ad-hoc and wrong decision concerning the selection and customization of OSS can result in severe negative consequences such as cost and schedule overrun [12].

The published empirical OSS research is aggregated and presented in the form of SLRs and systematic SMSs. These systematic secondary studies are on the diverse main topics of OSS like OSS evolution, OSS development, OSS Usage and OSS adoption, etc. Furthermore, one topic in turn covers varied topics e.g., OSS Evolution covers topics like OSS evolution w.r.t to time, OSS evolution (process and metrics), OSS evolution tools, etc.

The systematic secondary evidence available in the area of OSS points out topics, and future directions. However, the evidence present is not aggregated or classified. Collecting evidence is essential for recognizing the current state of the art and delineating future research directions in the broader field of open-source software (OSS) research. To address this issue of systematic secondary studies classification, a tertiary study is conducted.

This tertiary study makes the following contributions:

- It identifies the systematic secondary research conducted in the area of OSS.
- The research is mapped to the categories and subcategories of taxonomy already defined in the literature [2]. The details of the taxonomy are discussed later in the section of Background and Related work II.
- The future directions present in the systematic secondary studies are thematically analyzed [8] to present future research areas in OSS domain.
- These mapping of areas and future directions will help researchers to better guide and lead their research in open-source areas. The details of these implications are given in Discussion Section V under the heading "Implications of this Research for OSS Researchers".
- This study can also guide practitioners in making informed and useful decisions, as they are backed up by empirical evidence. The details of these implications are given in Discussion Section V under the heading "Implications of this Research for OSS Practitioners".

The remainder of the study is organized as follows, background and related work is discussed in Section II, Section III details the research method, and Section IV presents results of RQ1, RQ2, and RQ3. The discussion is presented in Section V, validity threats are stated in Section VI, and finally, the conclusion is given in Section VII.

II. BACKGROUND AND RELATED WORK

The concept of OSS gained popularity after the term Open-Source initiative was coined in 1998. A vast literature has been published on OSS research, its adoption, evolution, communities, etc. Four attempts are made to combine OSS research directions/areas into a form of a classification [7, 28, 35, 2].

The study [7] organizes OSS research into a framework from one hundred and eighty-four primary studies. It identifies the input, processes, emergent states, and outputs of the OSS model. The input is categorized into member characteristics (e.g., skills, personalities), project characteristics (i.e., license type), and the use of technology (i.e., type of technology used). The processes are the interactions between team members to convert input into output of a project. Processes include software development practices (e.g., project management), social processes (e.g., decision-making), and practices where firms are involved (e.g., adoption). The output is the "task and, non-task consequences of a team's function". The output is categorized as "software implementation (use of FLOSS in different contexts), team performance (e.g., success measures), and evolution (software and community evolution)", etc.

A semi-automated approach is followed in this research, covering OSS conferences for six years [28]. A semi-automated approach does "automated inspection of articles building cross-citation maps and then manually building knowledge blocks of OSS". The major areas of knowledge according to the interlinked clusters are the "studies on (FLOSS mole) project, quality assurance in OSS, involvement of volunteers in OSS projects, perception of OSS in industry, and also on OSS adoption, software evolution, security of OSS, OSS trustworthiness, process modeling, and the social structure of OSS communities". The isolated clusters are "innovation, adoption, services requirements, the success of OSS projects, and teaching OSS at the university level".

The systematic review [35] focuses on gaining insight into the state of practice of reporting empirical studies in OSS. It analyzes and categorizes the field into "OSS communities", "OSS development and maintenance", "diffusion and adoption of OSS" and "characteristics of OSS". The category that has ample research in the OSS domain is the OSS community, with work in sub-topics of the social network of communities, life cycle and community evolution, and communities' communication. The OSS development and maintenance are about the practices, and issues of OSS development. Furthermore, diffusion has sub-categories, i.e., "perception of OSS, the incentive to adopt OSS, migration to OSS, and usage of OSS". The characteristics of OSS cover "general characteristics, growth, evolution, and quality of OSS". These two mapping studies are also included in the secondary evidence of this tertiary study.

The most extensive work among all is a proposed taxonomy of OSS proposed by Aksulu and Wade [2]. Using an iterative coding process on a sample of 618 peer-reviewed articles, they developed a taxonomy of open-source research consisting of two levels - seven higher-level categories of topics addressed in their sample of articles and fifty-seven sub-categories under the seven main categories. The seven high-level categories are:

- Conceptual: The conceptual category includes six types of articles that 1) describe the background or evolution of OSS in general or a specific OSS, 2) discuss the benefits and drawbacks of using OSS, 3) provide a vision or road-map of OSS, 4) propose a categorization or future agenda of open-source research, 5) include some form of a comparison of OSS with proprietary software, and 6) propose economic models and policies explaining the OSS and its benefits.
- Performance Metrics: The performance category also includes six types of articles that 1) investigate different issues and factors related to software quality, 2) as a sub-topic under software quality, look into defect and bug handling processes within OSS teams, 3) as a sub-category under software quality, specifically investigate security factors in OSS, 4) study OSS code efficiencies and its comparison with proprietary projects, 5) investigate the performance of the individuals and teams working in the OSS projects, and 6) investigate OSS success factors.
- Legal and Regulatory: It includes four types of articles that: 1) investigate different types of OSS licenses, associated risks, and compliance issues, 2) look into the intellectual property rights and issues related to the OSS, 3) investigate legal issues related to the OSS including aspects such as open-source ownership, and 4) focus on various OSS standards and regulations.
- OSS Production: It covers articles that investigate different aspects related to the production of OSS. It includes fourteen types of articles that investigate: 1) the process of OSS development, 2) structure, formation, social and cultural aspects of OSS communities, 3) formation and management of OSS teams, 4) governance mechanisms of OSS communities, 5) team and project leadership, 6) learning practices in OSS projects for individuals and teams, 7) how OSS is contributing to innovation, 8) the role of volunteers - both users and developers, in OSS production, 9) collaboration and knowledge sharing mechanisms in OSS communities as compared to traditional organizational structures, 10) motivations of the participants in OSS communities, 11) what role commercial organizations play in OSS projects and what are their motivations, 12) the (re)- use of OSS components and its impact on software economics, 13) how different licensing and intellectual property types impact OSS developers, teams and projects, and 14) self - organization process in OSS - and its impact on the evolution of the community.
- OSS Applications: It includes articles that focus on OSS applications for different domains. The category includes articles about fifteen different application domains such as education, telecommunication, gaming, and operating systems.
- OSS Diffusion: The OSS diffusion category includes articles associated with adoption, and implementation, i.e., “1) OSS adoption - general, 2) OSS adoption barriers, 3) OSS adoption - decision factors, 4) OSS implementation - general, 5) OSS implementation - implementation communities, and 6) OSS implementation - governments/nations”.
- Beyond software: This category discusses open-source implications beyond software development. It includes articles on “1) Open paradigm, 2) Open innovation, 3) Open knowledge flows, 4) Open standards, 5) Open education, and 6) User or co-production of goods and consumer implications”.

The table 1 presents comparison of related work with tertiary study according to publication year, time frame, DARE quality assessment criteria [5] and Limitations.

This tertiary investigation differs and is more recent than the preceding research. The differences of related work with the tertiary study are evident from the table 1. The taxonomy of Aksulu and Wade [2] is the most relevant work, however it also have major differences with this tertiary study discussed below

- The taxonomy mentioned is a detailed work covering 618 primary studies (identified via ProQuest database, and snowballing technique) out of which 193 were selected whereas, this tertiary study includes seventy-four secondary studies out of 1976 from the main venues of CS, and SE which are IEEE, ACM, Springer Link, Science Direct, and Scopus via automated search, and snowballing technique.
- The research method used in the taxonomy is a qualitative analysis methodology where categories and sub-categories are identified from the data using Webster and Watson method [38] whereas, this research is performed systematically based on the guidelines of Kitchenham [20]. The themes and codes of future directions are identified using thematic analysis[8].
- The taxonomy has only used three search terms to identify relevant literature that are “open source software, open systems, and open source” whereas, the search terms identified and included in the search string by this tertiary study are very detailed as can be seen in the search strategy section III-B.
- The period of the taxonomy is not restricted by year, but it is an old work published in 2010, whereas, this research work is the state-of-the-art in OSR with search time between 2004-2022.
- The taxonomy has only categorized the research using descriptive and interpretive coding whereas, this re-

TABLE 1: Comparison of Related Work

Evaluation Criteria	Study [7]	Study [28]	Study [35]	Study [2]	Tertiary Study
Publication Year	2012	2011	2009	2010	Not Applicable
Time Frame	Till 2009	5 Years starting from 2005	Not Mentioned	Till 2009	2004-2022
Are inclusion/exclusion criteria reported?	Yes	Yes	Yes	Partial	Yes
Is the search adequate?	Partial	No	Yes	Yes	Yes
Are the included studies synthesized?	Yes	No	Partial	Yes	Yes
Is the quality of the included studies assessed?	No	No	Yes	No	Yes
Are sufficient details about the individual included studies presented?	Partial	Partial	Partial	Partial	Yes
Limitations of the Study	Time Period (Till 2009 Limited Time Frame (from 2006 to 2009) Search Process ((only Journal Articles in second wave) Analysis on Self Coding Scheme The Focus is OSS Development rather than OSR	Time Period (Till 2010) Limited Time Frame (2005 till 2010, 6 Years of Conference) Search Process (Only Covered OSS Conference Series) Mapping study with no detailed analysis	Time Period (Till 2009) Limited Time Frame (Only Conference papers for limited time) The reference to synthesis method is not given The focus is identifying state of the practice of reporting empirical studies of OSS to improve quality of evidence rather than OSR	Time Period (Till 2010) Not a Systematic Review Flaws of Taxonomy discussed in our Review Search Not specific to Computer Science and Software Engineering Domain	May miss important OSR area if not discussed in Systematic Secondary Study Research

search categorizes OSS research, and also discusses the main topics in these areas. Furthermore, it also identifies themes and codes of future directions using thematic analysis [8].

- The taxonomy has not performed any kind of quality assessment of the included studies where as this tertiary study has used the DARE quality assessment criteria [5] for detailed quality evaluation.

Initially, the researchers used thematic analysis [8] for the categorization of research areas, topics, and future directions in OSS. Major areas like OSS quality, OSS communities, OSS developers, OSS adoption, OSS evolution, and OSS process, etc. emerged as major themes using themetic analysis [9] . However, the taxonomy [2] provides a similar and relevant structure to classify OSS research, therefore, we used the taxonomy structure to classify the topics investigated in the systematic secondary studies of open-source research. To remain receptive to novel codes and themes, the future directions are thematically analyzed [8] instead of mapping to the already defined taxonomy of Akusulu and Wade [2].

The tertiary study is an attempt to update the categorization of open-source research in the area and this research aggregates evidence from 2004 till 2022. The categorization of areas and topics is done systematically via Kitchenham guidelines. The quality assessment of the systematic secondary studies is also performed using DARE Criteria. The recent future directions explicitly mentioned by the systematic secondary studies are also aggregated and presented in this study.

III. RESEARCH METHOD

A tertiary study follows the same process as that of an SLR. A systematic secondary study analyses primary studies, whereas a tertiary study aggregates and analyses evidence present in systematic secondary studies to highlight state-of-the-art. We followed the guidelines of [20, 9, 21] for conducting SLRs in software engineering to conduct this tertiary study.

A. RESEARCH QUESTIONS:

We have developed the following research questions to guide this tertiary study.

1) RQ1. What are the characteristics of systematic secondary studies on OSS research?
   a) RQ1.1 How many systematic secondary studies on OSS research are published to date?
   b) RQ1.2 Which individuals and organizations are involved in systematic secondary studies on OSS research?
   c) RQ1.3 What is the quality of systematic secondary studies on OSS research?
2) RQ2. Which topics are investigated in the systematic secondary studies on OSS research, and how can we classify them?
3) RQ3. Which future research directions are reported in the systematic secondary studies on OSS research?

B. SEARCH STRATEGY:

The primary search strategy is an automatic execution on Computer Science (CS) and Software Engineering (SE) databases which, is complemented by snowballing [24]. Snowballing involves scanning the references of the included studies (backward snowballing) as well as covering the citations of included studies (forward snowballing) to ensure better search coverage.

1) Identification of Venues and Databases:

We used automated search on the databases that publish all major software engineering conferences and journals. Five databases are selected (IEEE Xplore, ACM Digital Library, Science Direct, Springer Link, and Scopus). They are popular databases for CS, and SE research and are also used by the majority of the tertiary studies in software engineering (CF:[23, 37]).

2) Establish Quasi Gold Standard:

Zhang et al. [39] proposed the use of a Quasi - Gold Standard (QGS) to approve the search process. QGS consists of a “set of known papers” that are used to see if the search string can capture the relevant papers [39, 24]. To identify the QGS, we used the following search string in Google Scholar: “open source software” OR “free software” AND “systematic literature review” OR “systematic mapping study”. We scanned the initial twenty pages of the search results. Result Pages after twenty were found to be irrelevant. Through this process, we identified a total of twenty-three systematic secondary studies as QGS from a total of 9720 studies. Seventeen of the twenty-three studies are from ACM and IEEE. These databases are also selected for the piloting of the search string. These seventeen papers from ACM and IEEE are set as QGS and are available online at [1].

3) Define Search String:

We want to collect systematic secondary studies in the area of OSS as defined in research questions; thus, the main three search terms are: “open source”, “systematic literature review” and “systematic mapping study”.

The alternatives and synonyms of open source are identified from the studies found in QGS, which are:

“Open Source, Open - Source, Opensource, Open Source Software, Open Source Project, Open Source Software Project, OSS, OSSD, OSP, FOS, FOSS, FOSSD, FLOSS, F/OSS, F/OSSD, F/LOSS”

The synonyms and alternatives of the terms “SLR and SMS” are selected from the tertiary studies [26, 15]. The search terms are:

“Systematic Literature Review, Systematic Review, Systematic Map, Systematic Mapping, Mapping Study”

4) Pilot Testing of Search String:

The pilot testing is done on IEEE and ACM databases to check if the search string is providing relevant results [39]. A total of sixty-two search results are fetched - thirty-seven from IEEE and twenty from ACM. In total, we identified thirteen search results as relevant - ten from IEEE and three from ACM search results. The search string is validated by calculating the sensitivity and precision of the search results. The sensitivity of the search results is 76.4%, which is calculated by using the relevant search results (thirteen) and the set QGS (seventeen). Likewise, the value of precision is 20.96%, which is calculated by using the relevant search results (thirteen) and the total number of search results from ACM and IEEE (sixty-two).

The sensitivity and precision of the piloted string are more than the threshold value and fall in the acceptable range [39]. Thus, we decided to move forward in the search process

[1] https://www.scribd.com/document/612345196/QGS-Ieee-and-Acm

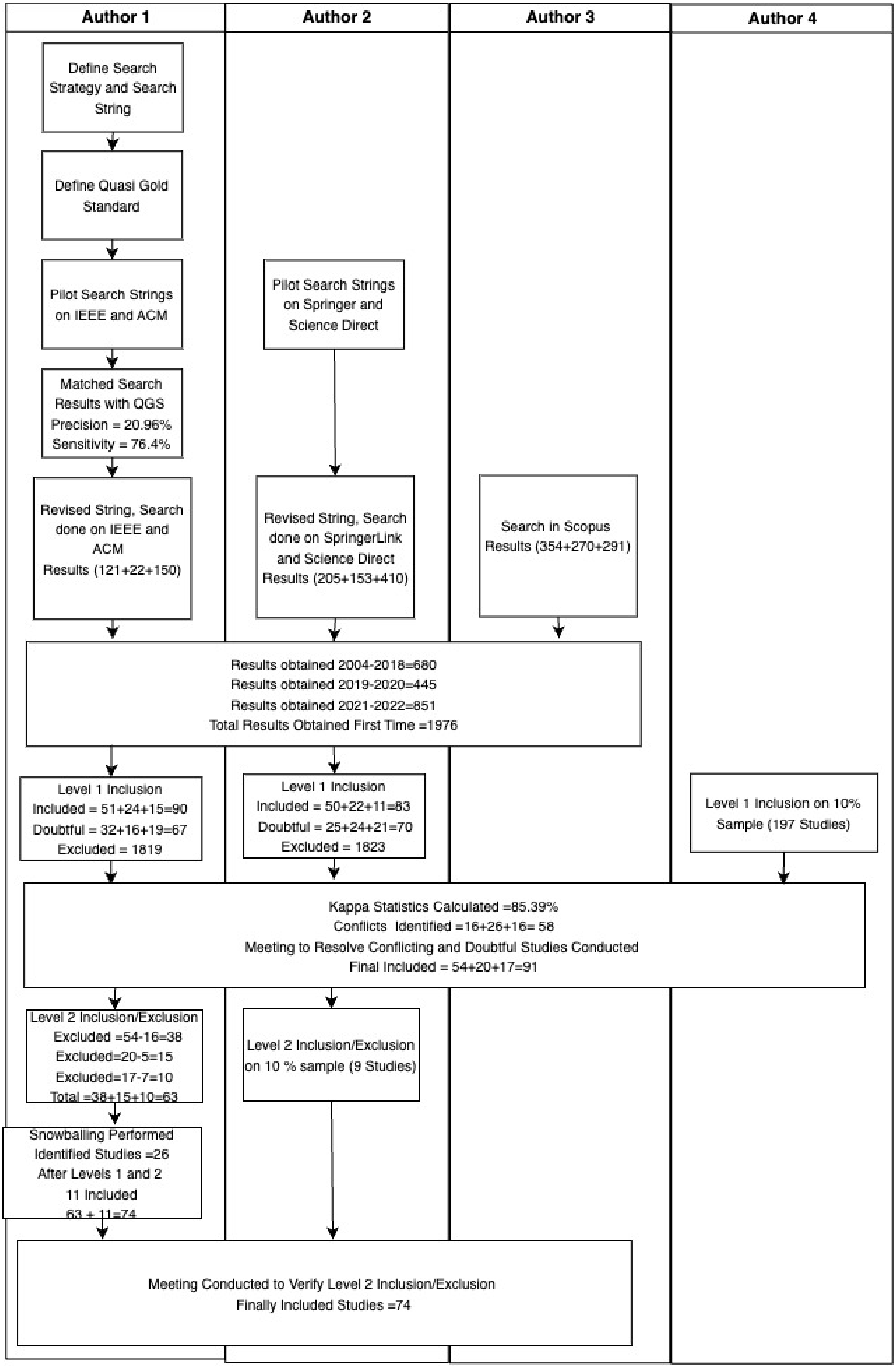

FIGURE 1: **Search and Selection Process**

by making only minor revisions to the search string. The analysis of the search results highlights that the terms like "OSP" and "OS" give irrelevant results, while the terms like "OSSD", "open-source software", "open-source software project", "open-source project", and "open-source" are covered by the main term open source and, therefore, are not needed. Similarly, the term "systematic map" is covered by the term "systematic mapping". The phrase "systematic literature review" is not used in double - quotes to include studies that have used keywords like "systematic review" and "literature review". The keyword "systematic literature review" also identifies traditional literature reviews; however, they are excluded in level 2 of the search strategy. A few studies used the term "free source" in the title and abstract of the study therefore, it is included in the final search string stated below:

("open source" OR "opensource" OR "free software" OR "free source" OR "libre software" OR "OSS" OR "FOS" OR "FOSS" OR "FOSSD" OR "FLOSS" OR "F/OSS" OR "F/OSSD" OR "F/LOSS") AND ("systematic literature review" OR "systematic review" OR "systematic mapping" OR "systematic map" OR "mapping study"))

The final search is performed on the titles, abstracts, and keywords in the selected electronic databases first in April 2019, then in November 2021, and finally in July 2023. These three searches cover search years from 2004 (when the first version of the guidelines for SLRs in SE were published) till 2022.

5) Conduct Automated Search:

The final search string is customized and executed on each selected database. The search results are saved in Zotero [2]. The automated search is also complemented with a manual search via snowballing technique to ensure maximum coverage of the literature [36].

C. STUDY SELECTION PROCESS:

The inclusion/exclusion criteria is given below:-

- IC1 - It is published in a peer - reviewed conference, journal or workshop
  EC1 - It is not published in a peer - reviewed conference, journal or workshop
- IC2 - Is published from 2004 till 2022
  EC2 - It is published before 2004
- IC3 - It is reported in English
  EC3 - It is not reported in English
- IC4 - It is either an SLR or SMS
  EC4 - It is not an SLR or SMS
- IC5 - It is about a research topic related to OSS
  EC5 - It is not on a topic related to OSS that is
  - EC5.1 Studies that just use OSS for validation/evaluation purposes
  - EC5.2 The focus of the study is on some other topic
  - EC5.3 The focus of the study is on individual OSS systems and projects

The study selection process is performed at two levels. At level 1, the inclusion and exclusion criteria are applied to the title and abstract of the candidate's primary study. At level 2, the study selection is performed on the full text of the candidate primary study.

1) Level 1 Study Selection:

Level 1 study selection is performed by two authors independently to remove bias. The fourth author validated the study selection process by applying the inclusion/exclusion criteria to a randomly selected sample (10%). The disagreements are discussed in a meeting by the first, second, and fourth authors to reach a consensus. The disagreements are minimal, i.e., only fifty-eight disagreements out of a total of 1976 - resulting in a kappa value of 85.39% [13], reflecting a good level of agreement between the authors.

2) Level 2 Study Selection:

During level 2 study selection, the inclusion and exclusion criteria are applied to the full text of the candidate's primary studies. The reason for excluding a study at level 2 is also documented. The first author performed level 2 study selection on all candidate primary studies, while the second author validated a randomly selected sample (10%). The disagreements, (eighteen), are resolved in a meeting with the third author. After level 2 study selection, sixty-three studies are included as primary studies. We also performed snowballing [36] on these sixty-three included studies, which resulted in the identification of twenty-six new studies. Most of the studies identified as relevant via snowballing are already included as a result of the initial automated search. Finally, eleven studies are included as a result of snowballing, making a total of seventy-four studies.

D. STUDY QUALITY ASSESSMENT:

We used the Database of Abstracts of Reviews of Effects (DARE) criteria for assessing the quality of the systematic secondary studies included in this study [5]. The DARE criteria are frequently used in SE to evaluate the quality of systematic secondary studies [4, 23, 26, 10, 37].

The SMSs are assessed on three questions, excluding the questions related to synthesis and quality assessment, as they are normally not part of a mapping study as opposed to an SLR [9]. However, nine SMSs have performed the synthesis and three SMSs have performed the quality assessment.

The SLRs are assessed on the complete five question of DARE quality criteria [5]. Eight SLRs have not mentioned or defined any synthesis method, twenty SLRs have not performed quality assessment, and four of the SLRs have neither synthesis nor quality assessment. The details are discussed in results and discussion of RQ 1.3.

[2] www.zotero.org

The quality assessment is performed by the first author, which is validated by the second author on a randomly selected sample (10%).

- 10% means 10% out of 74 papers (the total number of included studies), which came out to be 7.4 (but we rounded it up to 8).
- Out of these eight papers that were also reviewed by the second author, 5 quality questions had disagreements between first and second author.

The complete quality assessment scores are available online at [3].

E. DATA EXTRACTION PROCESS:

The data extraction form is designed, keeping in view the research questions. The data extraction form is piloted by extracting data from a sample of three studies - one SLR by the first and third authors and two SMS by the first and second authors. The data extraction form is updated as a result of the piloting phase. The findings are further categorized into general findings, specific to the research question, and findings in our own words. A new field added is "*need to establish review*". The field is added as it is a very important aspect of planning a review according to the guidelines of performing SLRs in software engineering [18]. The data extraction form is available online at [4].

A study reported in more than one publication is counted as one. If the study is reported in both a conference and a journal publication, the journal publication is included. Moreover, if a study is published in two conference publications, the one published recently is considered.

The roles of the authors with responsibilities are explained online at [5].

F. ANALYSIS PROCESS:

The analysis process followed for the classification of key areas and topics of OSS research is a detailed categorization defined in the area of OSS via OSS taxonomy [2], whereas, future directions are analyzed using thematic analysis [8].

For RQ2 related to topics in OSS research, we also used the OSS taxonomy [2], to classify the OSS research reported in seventy-four included systematic secondary studies. To guide the synthesis work, the approach proposed by Ryan and Bernard is used [32], wherein the work is mapped to already defined categories found in the literature. The findings are classified into these categories and sub-categories using scrutiny, cutting sorting, and meta-coding techniques [32]. These techniques help in analyzing and categorizing data by carefully reading the whole paper and marking things of interest. These markings are then cut and sorted according to the already defined categories and sub-categories.

For future research directions, RQ3, we used the thematic analysis [8] to analyse and present results. The future directions are extracted from the papers, coded, and categorized in themes via thematic analysis. A different approach of thematic analysis is followed for future directions, to remain receptive to novel codes and themes.

The first author led the analysis process of RQ2 including the mapping of the identified topics on the OSS taxonomy categories and sub-categories whereas, the second author validated it on a 10% random sample. Initially, few studies were mapped during piloting, and the results were discussed with the fourth author in a meeting. The piloting stage clarified the mapping strategy, which helped the first author to map the complete set of studies to the taxonomy. The studies which could not be mapped by the first and second authors (eight studies) were discussed in a meeting with the first and third authors, and mapped accordingly. Finally, there were fifteen disagreements in the topic - related mapping (RQ2), which were resolved within a meeting of the first and third authors. The final mapping of systematic secondary studies (seventy-four) to the taxonomy [2] is available online at [6]

Similarly, for RQ3, the first author led the thematic analysis and identified codes and themes of future directions whereas, the second author validated it on a 10% random sample. The disagreements were minimal, which were later discussed in a meeting, and issues were resolved via consensus.

IV. RESULTS

The study results are based on a total of seventy-four systematic secondary studies: forty-nine SLRs and twenty-five SMSs, covering a variety of OSS research topics. The search covers the period from 2004 (when the first version of the guidelines for performing SLR in software engineering by Kitchenhem was published) till 2022.

In the subsequent sections, we present the results for each of the research questions.

The full list of the included studies is provided online at [7]

A. RESULTS RQ1: WHAT ARE THE CHARACTERISTICS OF SYSTEMATIC SECONDARY STUDIES ON OSS RESEARCH?

RQ1.1 aims to see how seventy-four systematic secondary studies included in the tertiary study are spread over the timeline: of 2004-2022. Figure 2 shows the distribution of the identified studies over this timeline.

[3]https://www.scribd.com/document/672785433/Complete-Quality-Scores

[4]https://www.scribd.com/document/612345186/Data-Extraction-Form-Tertiary-Study-on-OSS

[5]https://www.scribd.com/document/672783007/Data-Extraction-and-Synthesis-Process

[6]https://www.scribd.com/document/672787040/Taxonomy-Mapping-Online-Updated

[7]https://www.scribd.com/document/672785323/List-of-All-Include-Studies

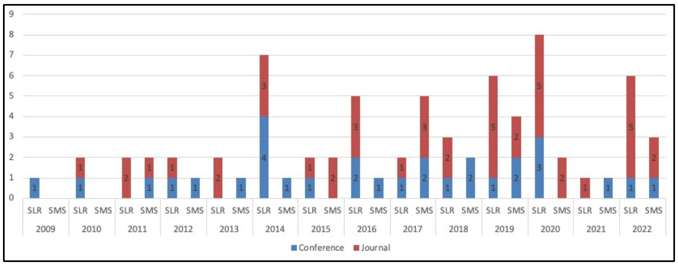

FIGURE 2: **Year - wise Distribution of Type of Studies**

The first SLR in the sample on OSS research is published in 2009-five years after the publication of the first version of the guidelines [20] for conducting SLRs in software engineering. Between 2009 and 2013, there are around two to three SLRs/SMSs on OSS research every year. Figure 2 shows an upward trend in the publications on systematic secondary studies on OSS research in 2014 and then from 2016 onwards till 2022. The Year 2019, 2020, and 2022 have especially high number of SLRs and SMSs published in journals.

We attempted to capture which years are most thoroughly covered in the search phases of the systematic studies included in the review. Figure 3 shows that more than half of the systematic secondary studies in the sample (i.e., close to forty) have covered the years between 2003 and 2013 in their searches. The year 2010 holds the highest coverage, encompassing fifty studies. Expanding the timeline, we also notice that the years 2000 to 2020 are covered by at least 10 systematic secondary studies on OSS research. It shows that the primary evidence on OSS research published between 2000 and 2020 is quite thorough. Understandably, recent years (2021-2022) are not covered in many studies so far.

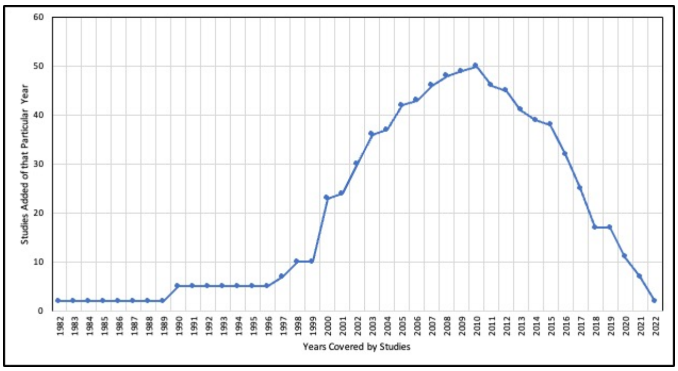

FIGURE 3: **Years covered in the searches of Systematic Secondary Studies on OSS research**

A thorough examination of secondary studies also reveals a deficiency in primary research within the domains of Software Quality, OSS Standards, Team Formation, and OSS Applications. Systematic secondary studies S8, S31, S32, S61, S62, and S67, collectively analyzed 36, 29, 17, 36, 6, and 51 primary studies, respectively. In the domain of OSS standards and regulations, systematic secondary studies S40 and S45 encompass 17 and 18 primary studies. Two systematic secondary studies, S9 and S65, aggregate a total of 20 and 46 primary studies in the realm of Team Formation. The utilization of OSS in Biomedical and Health Sciences appears restricted, as indicated by systematic secondary studies S30, S34, and S44 include 21, 17, and 47 primary studies only. The domain of volunteer/user/developer has systematic secondary research S63 and S70 with 51 and 10 primary studies respectively. Each of these thematic codes presents a promising future direction for OSS scholars evident from the limited number of primary studies.

RQ1.2 aims to identify the authors, and their corresponding countries, who have published systematic secondary studies on OSS research. Table 2 presents countries, the number of publications, and, the prominent authors (having more than one SLR/SMS publication) from the respective countries. The highest number of systematic secondary studies on OSS research is published by authors from Brazil (thirteen studies), which is more than double the number of publications by the second country on the list, i.e., Sweden (six studies). The next countries are Spain and Finland (five studies). The countries, Ireland, India, and the USA each have four studies. Table 2 also lists the authors who have contributed to two or more systematic secondary studies on OSS research. The results show that several researchers have published multiple systematic secondary studies on OSS research.

In RQ1.3, we assessed the quality of the included systematic secondary studies on OSS research using DARE [5], which is the most commonly used quality assessment criteria in SE tertiary studies. We used Verner et al. [37] interpretation of the DARE criteria to assess the quality of the included systematic secondary studies. The interpretation is available online at [8]

Figure 4 shows the ranking of SLRs and SMSs on the five DARE question [5]. The study selection criteria - DARE Q1 - is reported by the majority of the studies in our sample (thirty-nine out of forty-nine studies) with, only five SLRs not defining the inclusion /exclusion criteria, and five SLRs have implicitly defined inclusion/exclusion criteria. With respect to the detailed and adequate definition of the search process in the SLRs, the results highlight that the majority of the SLRs have fully/partially defined search process (twenty-two and twenty-five respectively). The synthesis Q3, and quality assessment Q4, are the two criteria that separate an SLR from a scoping or mapping study. The results show that twelve SLRs in our sample have not performed synthesis at all, and half of the SLRs have not performed quality assessment. The DARE-Q5 criterion is mostly fulfilled by the SLRs (thirty-four out of forty-nine). The SLRs that lack quality assessment and synthesis may better be classified as mapping studies. We have introduced a separate section for those SLRs.

[8]https://www.scribd.com/document/672784679/Table-DARE-Quality-Criteria

TABLE 2: **Prominent Countries of Publication and Authors having Systematic Secondary studies on OSS Research**

Country	Number of Publications	Authors having multiple systematic secondary studies on OSS research
Brazil	13 (in all, the first author is from Brazil)	Edna Dias Canedo (3), Christina Von Flach G Chavez (2), Debora C. Nascimento (2), Roberto A. Bittencourt (2), Igor Steinmacher (2), Igor wiese (2), Marco Aurelio Gerosa (2)
Sweden	5 (in 5/6, the first author is from Sweden)	Alma OruČević - Alagić (2), Martin HÖst (2)
Spain	5 (in 4/5, the first author is from Spain)	Oscar Franco - Bedoya (2), David Ameller (2), Dolors Costal (2), Xavier Franch (2)
Finland	5 (in 4/5, the first author is from Finland)	M.M.Mahbubul Syeed (2), Imed Hammouda (2), Tarja Systa (2)
Ireland	4 (in all, the first author is from Ireland)	Henry Edison (2), Noel Carroll (2), Kieran Conboy (2), Lorraine Morgan (2)
India	4 (in all, the first author is from India)	Munish Saini (3), Kuljit Kaur Chahal (3)
USA	4 (in 2/4, the first author is from the USA)	
Canada	3 (in 3/6, the first author is from Canada)	Alain Abran (2)
Malaysia	3 (in all, the first author is from Malaysia)	Abdul Azim Abd.Ghani (3), Hazura Binti Zulzail (3)
Norway	3 (in 3/5, the first author is from Norway)	
Iran	3 (in all, the first author is from Iran)	
Pakistan	3 (in all, the first author is from Pakistan)	
Italy	3 (in 2/3, the first author is from Italy)	
Portugal	3 (in 2/3, the first author is from Portugal)	
Turkey	3 (in 2/3, the first author is from Turkey)	
Australia	2 (in all, the first author is from Australia)	
Columbia	2 (in all, the first author is from Columbia)	
Germany	2 (in all, the first author is from Germany)	
Morocco	2 (in all, the first author is from Morocco)	
UK	2 (in 1/2, the first author is from UK)	
Denmark	2 (none of the publication has the first author from Denmark)	
All the countries having one publication in the area		
Belgium, Chile, Chine, Ecuador, Estonia, Nigeria, Poland, Peru		
South Africa, UAE, and Yemen		

The SMSs are evaluated using three questions from the DARE quality criteria (DARE), as synthesis and quality assessment are not mandatory steps in the SMS. However, eight of the SMSs in our sample have conducted a synthesis (completely or partially), and three SMSs in our sample have also performed the quality assessment. Similar to the SLRs, almost all the SMSs have defined inclusion/exclusion criteria (twenty-four out of twenty-five). It is seen that fourteen SMSs have defined the search process in detail and eleven of the SMSs have partially defined it. The scores of Q5 show that most of the SMSs have described the included studies in detail.

We included all systematic secondary studies in this tertiary study since the objective of this research is to identify and categorize the state-of-the-art of OSS research. We have reported the quality scores of all studies available online, which will help researchers to identify, for example, those SLRs that do not have any synthesis or quality assessment and may therefore be viewed as scoping studies, rather than complete SLRs.

B. RESULTS RQ2: WHICH TOPICS ARE INVESTIGATED IN THE SYSTEMATIC SECONDARY STUDIES ON OSS RESEARCH, AND HOW CAN WE CLASSIFY THEM?

In this research question, we identify, describe, and categorize the topics investigated in the systematic secondary studies on OSS research. We used Aksulu and Wade's taxon-

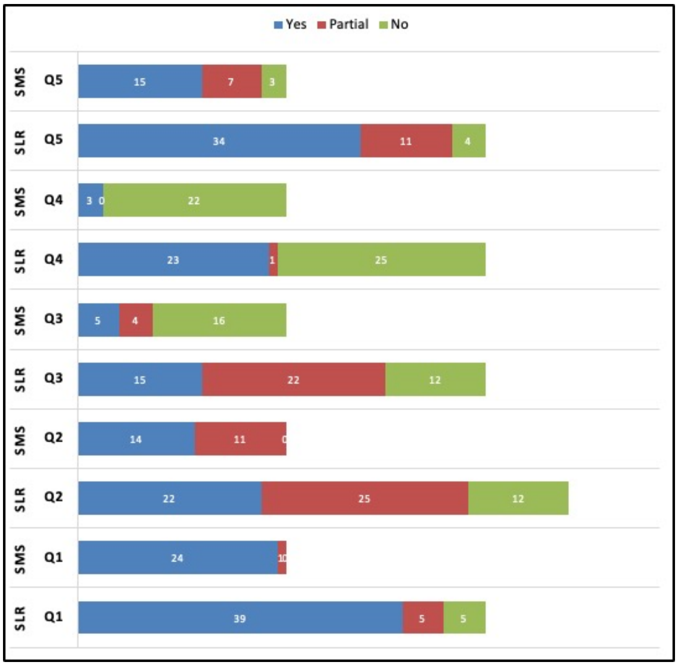

FIGURE 4: **Quality Assessment Score of Each Research**

omy [2] to classify the topics investigated in the systematic secondary studies in our sample. As described previously in Section II, the taxonomy consists of seven main categories and fifty-seven sub-categories. We present the classification of the seventy-four systematic secondary studies based on the seven main categories of the OSS taxonomy (see Figure 5).

The results show that the most investigated topics by the systematic secondary studies on OSS research in our sample are from the "*Conceptual*" and "*OSS Production*" categories. The topics related to "*OSS Applications*", "*Performance Metrics*", and "*OSS Diffusion*" are also investigated in few studies in our sample. The results show that the topics related to the "*Legal and Regulatory*", and "*Beyond Software*" categories are only investigated by a handful of studies in our sample. We now discuss these categories in detail and see what specific sub-categories and topics related to these categories are investigated in the systematic secondary studies.

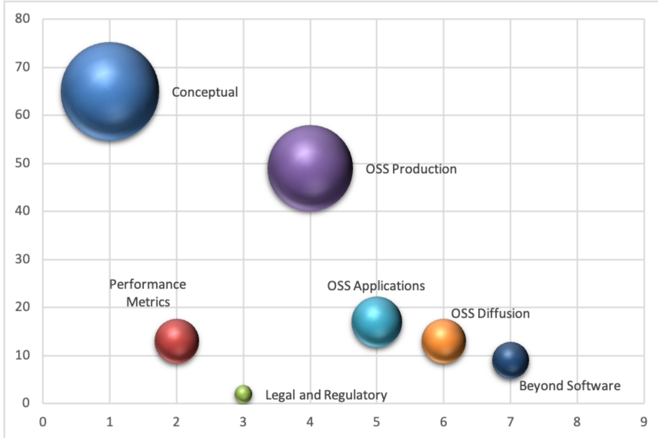

FIGURE 5: **Frequency of studies mapped to the categories of OSS Taxonomy**

1) Conceptual:

A total of sixty-five systematic secondary studies in our sample have investigated topics related to the conceptual category of OSS taxonomy [2]. The conceptual category has six sub-categories (see section II for details). We now describe what topics are investigated in the systematic secondary studies on OSS under these sub-categories.

a: OSS Research Categorization/Research Agenda:

Most of the included studies are present in this sub-category with twenty-nine studies presenting research categorization, state-of-the-art of OSS is discussed in eleven studies, and OSS frameworks, and taxonomy are given in three studies. Four of the studies have both state-of-the-art and categorization. The most researched topic inside the conceptual category is OSS adoption categorized in S7, S8, S36, S41, S47, S49, S55, S63, and S68. The studies S7, and S41 define frameworks for organizations, to adopt OSS and FLOSS. The study S8 gives the state-of-the-art of predicting projects from the perspective of code and community that are required for the successful adoption of OSS. The study S36 identifies the state-of-the-art of risk analysis of OSS adoption whereas, study S47 categorizes OSS evaluation, selection, and adoption models and factors. OSS adoption factors are also identified and characterized by study S49 and success factors for adapting OSS are discussed by study S55. Study S63 categorizes women's participation in OSS development, and study S68 categorizes research of OSS with GitHub.

The second major research categorization is of OSS community/developer's involvement in OSS, having studies S9, S25, S50, S57, S58, S60, and S65. The area of community and developer perspective focuses on barriers faced by the newcomers discussed by study S9 knowledge loss problems of OSS communities along its impact on OSS projects is identified by the study S25. The study S50 includes an overview of the community dynamics in OSS projects, and categorization of developer forking motivational behaviour,

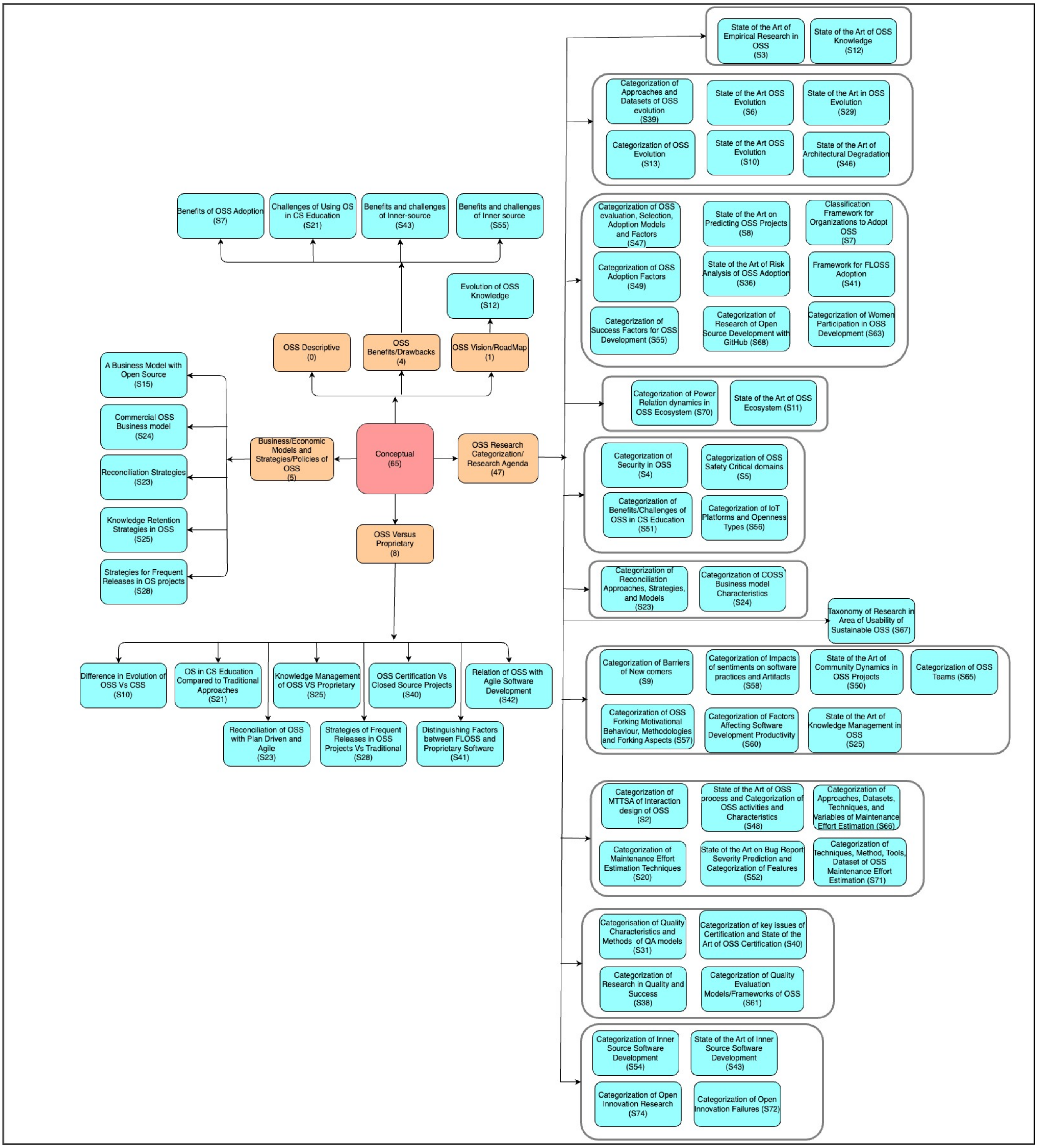

FIGURE 6: **Category: Conceptual**

forking methodologies, and forking aspects of the community is discussed in S57. The authors of the study S58 examine the impact of the developer sentiments on software practices/ artifacts. The study S60 identify factors that impact a developer's productivity. Furthermore, the study S65 presents categorization of OSS teams.

The research categorization of OSS evolution is done in studies S6, S10, S13, S29, S39, and S46. The state-of-the-art in OSS evolution is presented in S6, S10, and S29, categorized by the study S13. The study S39 presents categorization of different domains, facets, and approaches, etc. of OSS evolution whereas, the study S46 categorizes solutions of architectural degradation.

The use of OSS in various domains and its categorization is performed in the studies S4, S5, S51, and S56. The study S4 categorizes security areas, their socio-technical aspect, and knowledge problems/resolution. Another study S5 categorizes safety-critical domains whereas, the study S51 identifies the benefits and challenges of OSS if used for Computer Science (CS) education. The study S56 identifies categories of Internet of Things (IoT) platforms and their openness types.

Studies that discuss the OSS development process and categorize it according to different aspects are S2, S20, S48, S52, S66, and S71. The study S2 discusses the use of methods, tools, and techniques for interaction design in OSS. Another study S20 categorizes the sub-activity of maintenance effort estimation techniques. The study S48 presents the OSS development process and categorizes the activities of OSS development, and, the study S52 discusses bug report severity level prediction in OS projects for effective planning of maintenance and evolution. The study S66, and the study S71 presents the categorization of approaches, techniques, datasets, and methods, etc. of maintenance effort estimation.

Four studies S31, S38, S40, and S61 discuss the quality aspect of OSS with focus on the categorization of quality characteristics, methods, and domains of the quality assessment models done by the study S31. The study S38 relates quality and success, and the study S40 presents a categorization of the key issues of certification to ensure quality. The categorization of quality evaluation models/frameworks is done in S61.

Four studies S43, S54, S72, and S74 present an overview and classification of inner source software development. The authors in the studies S3, and S12 highlight the OSS research area in general, and two other studies S11, and S70 focus on OSS ecosystem.

The study S23 characterizes reconciliation between three models of software development that are plan-driven, agile, and free/OSS. In this study, the authors characterize approaches, strategies, opportunities, challenges, and proposals for reconciliation. In another study S24 categorizes business models for commercial OSS. Finally, the study S67 presents a taxonomy of areas of usability of sustainable OSS.

b: OSS Versus Proprietary:

The second sub-category inside the conceptual category has 8 studies S10, S21, S23, S25, S28, S40, S41, and S42, that consist of studies that compare various aspects of OSS with proprietary or Closed Source Software (CSS). The study S10 on the topic of OSS evolution also contains a portion of analysis that compares the process of evolution with CSS. The study S23 compares OSSD with plan-driven and agile, whereas, the study S42 compares OSSD with agile only. The study S25 compares knowledge management in OSS and CSS. Another study S28 compares OSS and traditional development on release strategy.

The study S40 describes the certification process of OSS and CSS as product-focused and process-focused respectively. Finally, study S41 presents differences between FLOSS and proprietary software.

c: Business/Economic Models and Strategies/Policies of OSS:

The sub-category has five studies that are S15, S23, S24, S25, and S28. The studies which talk about business models of OSS in commercial organizations are S15, and S24. Three studies S23, S25, and S28 discuss different types of strategies in the OSS area. The study S15 discusses business models available for the use of OSS in product development, and presents challenges and, strategies of business around OSS.

The study S24 describes the elements of the Commercial OSS (COSS) business model, and categorizes them. The study S23, as described earlier, presents a reconciliation among agile, OSS, and plan-driven development. Most of the reconciliation is focused on the adaptation of models, practices, process improvement framework, etc. The study S25 presents knowledge retention strategies, and techniques used to capture knowledge based on knowledge sharing. Finally, the study S28 presents strategies to implement rapid releases in OSS.

d: OSS Benefits/Drawbacks:

The sub-category of OSS benefits/drawbacks incorporates literature consists of benefits/drawbacks and risks of using OSS in different domains. There are four studies S7, S21, S43, and S55 in this sub-category. The study S7 presents the advantages/disadvantages of using OSS in commercial organizations. It also presents the advantages of OSS adoption. The study S21 highlights the advantages and challenges of the use of OSS in CS education. Another study S43 discusses the benefit of using Inner Source Software (ISS), and also reports challenges. Finally, the study S55 presents success factors for OSS development.

e: OSS Vision/Road Map:

There is only one study S12, in our sample that discusses the state-of-the-art in the area of OSS in general with a focus on OSS future research. This study identifies promising areas of research.

2) OSS Production:

Forty-nine studies fall into fourteen sub-categories of OSS production [2]. The majority of the publications cover the area of OSS communities, process, user and developer motivation, and community evolution. The frequency of published secondary work inside the OSS production category is presented in Figure 7.

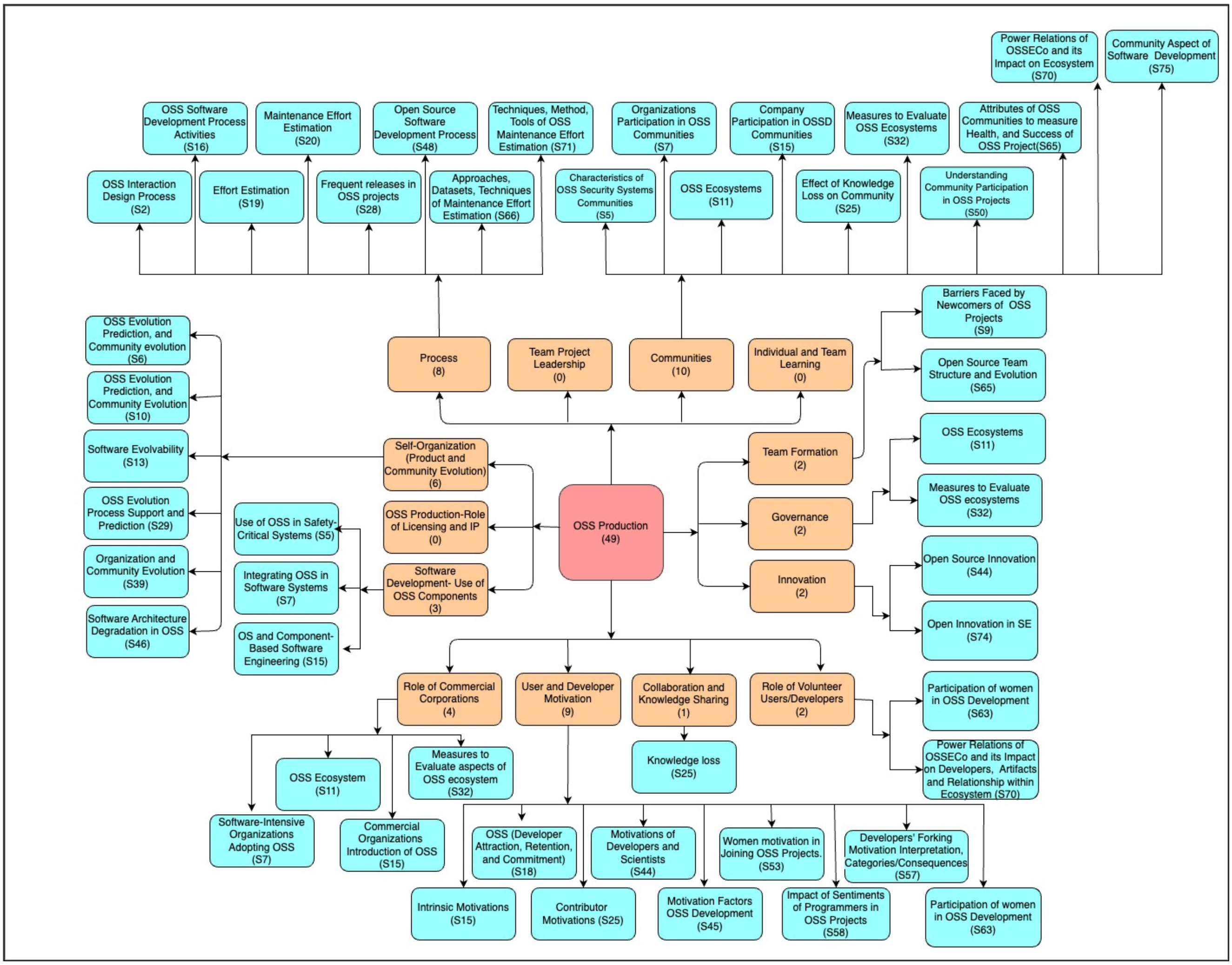

FIGURE 7: **Category: OSS Production**

No secondary research exists in the sub-categories of "*individual and team learning, team/project leadership, and OSS production-role of licensing and IP*". Limited research exists in sub-categories of "*role of volunteer Users/developers, innovation, collaboration and knowledge sharing, governance, and team formation*". The research trends in the sub-categories having systematic secondary studies are discussed below.

a: Communities/ Role of Commercial Corporations:

The two sub-categories "Community" and "Commercial Corporations" are identified and listed separately in the taxonomy. However, in literature, they are discussed collectively, thus presented together.

The study S5 identifies numerous community contributors in the area of safety-critical systems. The study S7 discusses the fact that organizations help communities by contributing to various OSS products. It also identifies collaboration between communities and commercial organizations. The studies S11, and S32 define the OSS ecosystem, thus having research about OSS communties as well. Another study S15, also discuss the collaboration between organization, and communities. The study S25 discusses the impact of turnover on the community, and identifies OSS organization structure as dynamic. Study S50, defines community participation and engagement research focusing on five sub-areas as "joining process, contribution barriers, motivation, retention, and abandonment".

The study S70 identifies various forms of power and dynamics within an OSSECO (Open Source Software Ecosystem). This understanding of power distribution allows community members to make decisions aligned with their objectives within the ecosystem.

Another study S65 categorizes OSS projects with respect to their structure, lifecycle and communication. Finally, the study S68 groups research into four main areas of development, projects, users, and the GitHub ecosystem. It covers a range of topics, like software development practices, project management, community aspects of software development, and the impact of GitHub on software development.

b: User and Developer Motivation:

Nine studies S15, S18, S25, S44, S45, S53, S57, S58, and S63 discuss the user and developer motivation in OSS projects. Study S15 discusses research focusing on developer attraction. Another study S18 identifies the extrinsic motives of FLOSS developers. The study S25 identifies community contributions, and the study S44 states the frequency of contributions, and the different motivations of the programmers and scientists. The study S45 states that intrinsic motivational factors for choosing an OSS license. Another area of research defined in the study S53 is the participation of women in OSS projects, and the study S58 provides clarity on influence of developer's sentiments on software practices. Finally, the study S57 defines the project forking concept in detail.

c: Self-Organization (Product and Community Evolution):

OSS evolution is a much-researched topic with the six studies that are S6, S10, S13, S29, S39, and S46 covering OSS evolution from either product or community perspective. Two studies, S6, and S10, discuss techniques used for OSS evolution analysis. Two studies S6, and S10, discuss the tools/techniques used for OSS evolution analysis. The study S13 categorizes OSS evolution literature whereas, the study S29 is a mapping study identifying the metrics for evolution prediction, and research on OSS evolution process support.

There is another study S39, on OSS evolution classifying evolution into the different categories. It also identifies, metrics to measure community evolution. The study S49 discusses the most common causes, and key indicators of architecture erosion in OSS projects.

d: Process:

The study S2 discuss "Methods, Techniques, Tools, Strategies, and Approaches (MTTSA) of interaction design in OSS". The study S16 compares the OSS process with IEEE standard 1074:2006. Another study S28 defines frequent releases in OSS. The study S48 classifies the OSS development process into activities and align with external environmental factors. The study S61 identifies ample research in the area of OSS effort estimation. Finally, studies S66, and S71 categorize techniques, tools, variables, etc. in the area of OSS maintenance effort estimation.

e: Software Development-Use of OSS Components:

Three studies S5, S7, and S15 discuss the use of OSS components. The study S5 states the OSS operating systems are used in automotive and medical domains with OS imaging functionality commonly used in safety-critical systems. The study S7 also states that the most popular method of OSS adoption is the integration of OSS components. In the study S15, the authors discuss the process of OSS industry users in the selection of off-the-shelf components (OTS) and, associated challenges for maturing the open-source component market.

f: Governance:

The studies S11, and S32 define the OSS ecosystem, therefore included in the sub-category of governance. The details are already discussed in the sub-category "*OSS Communities*" in the category of "*OSS Production*".

g: Team Formation:

The study S9 defines the barriers and social interaction problems of newcomers faced while contributing to OSS. The study S65 identifies open-source team structure and evolution, and is already defined in the sub-category "OSS communities" of category "OSS Production".

h: Role of Volunteer Users/Developer:

Two studies, S63, and S70 define women participation in OSS projects, identifying their challenges and strategies to overcome these challenges.

i: Collaboration and Knowledge Sharing:

The study S25 presents a detailed discussion on knowledge management, creation, sharing, and retention of OSS and is already discussed in the sub-category "*OSS Versus Proprietary*" in the category of "*Conceptual*".

j: Innovation:

The study S44, and S77 are in the area of Open innovation.

3) OSS Applications:

Seventeen studies are on the category of OSS application, having fifteen sub-categories. Moreover, many domains such as repositories, imaging, security, cyber-crime, supply chain management, optimization, simulation, academic, commercial research, natural sciences, public sector, and e-government have no published secondary evidence. The mapping of studies is discussed one by one.

a: Education:

Five studies describe the use of OSS in education that are S1, S21, S33, S51, and S59. The benefits of using OSS in education are stated by study S1, whereas, the study S33 discusses the detailed analysis of the education of graduate and engineering courses via OSS.

The study S51 also identifies the motivational factors for the use of OSS, and team motivation. The challenges associated with the use of OSS are also elicited in this study. The study S59 focuses on the improvements of OS development practices, and presents challenges encountered by software engineers with distributed software development practices. It also highlights factors that impact the success of beginners in open-source projects, and finally, the pros and cons of OSS adoption are also seen.

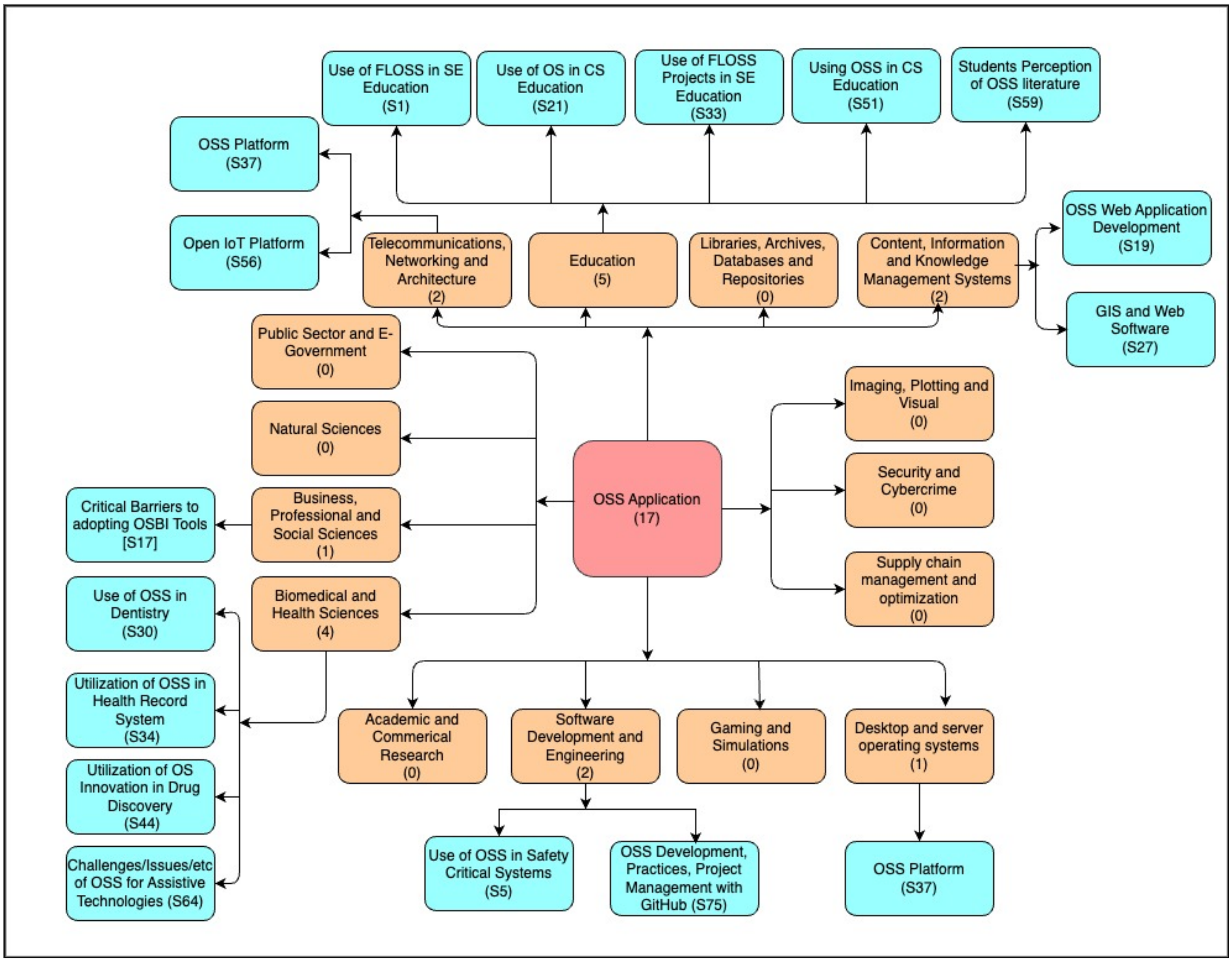

FIGURE 8: **Category: OSS Applications**

b: Biomedical and Health Sciences:

The area of biomedical and health sciences has four studies S30, S34, S44, and S64. The study S30 identifies limited research in the use of OSS in dentistry, with only few expert opinion and case-control studies. The study S34 identifies the motivation for the use of OS Electronic Health Record (EHR) systems. Another study S44 discusses the OSS model application to the drug discovery industry or patent-heavy industry. It identifies the benefits of the OSS model applications. The study S64 presents the usage, challenges, issues, and opportunities of OSS Assistive Technologies (AT).

c: Telecommunications, Networking, and Architecture:

Two studies, S37, and S56, fall in this area. The study S37 discusses open-source platforms whereas, the study S56 identifies that the publications on open IoT platforms.

d: Content, Information, and Knowledge Management Systems:

Two studies S19, and S27 fall in the application area of content, information, and knowledge management systems. The study S19 defines techniques for effort estimation of OSS web applications already present in the "*Business/Economic Models and Strategies/Policies of OSS*" sub-category in the "*Conceptual*" category. The study S27 is on Geographic Information Systems (GIS), with focus on the estimation exploring architectures that integrate open-source components.

e: Desktop and Server Operating Systems:

The study S37 is on OSS Platforms and is also mapped to the sub-category "*Telecommunications, Networking, and Architecture*" in the category of "*OSS Applications*".

f: Software Development and Engineering:

In the study S5 safety-critical systems are discussed, and the study S68 presents the OSS development and management practices with GitHub.

g: Business, Professional, and Social sciences:
The S17 discusses that Open-Source Business Intelligence (OSBI) tools. This study has also identified barriers faced to adoption that are discussed in the sub-category "*Adoption Barriers*" in the category of "*OSS Diffusion*".

4) OSS Diffusion:
Thirteen studies are mapped to the category of "OSS diffusion", having six sub-categories. The work is mapped to "OSS adoption, OSS adoption barriers, and OSS adoption decision factors". The categories related to OSS implementation do not have any study mapped to them. The included studies are mapped to the sub-categories of OSS diffusion in Figure 9.

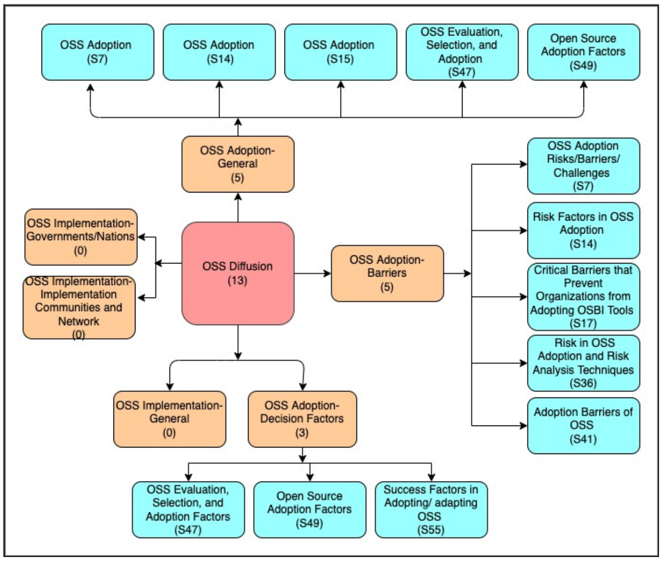

FIGURE 9: **Category: OSS Diffusion**

The trends in sub-categories having systematic secondary studies are discussed below.

a: OSS Adoption-General):
The study S7, and S14 classifies OSS adoption literature. The study S15 highlights the complexity of configuring a user environment in the area of OSS in product development, where product development is done with OSS instead of adopting OSS.

Two studies S47, and S49 identify models and factors related to adoption discussed in the sub-category "*OSS Adoption-Decision Factors*" in the category of "*OSS Diffusion*".

b: OSS Adoption-Barriers:
The study S7 identifies adoption barriers contributing to OSS products. The study finds that each organization has different motivations and resources to adopt OSS. The study S14 identifies and presents OSS adoption risk factors whereas, study S17 discusses the adoption of business intelligence tools. Another study S41 classifies OSS adoption barriers, and areas where OSS adoption is increasing. Finally, the study S36 identifies different risks in OSS adoption

c: OSS Adoption-Decision Factors:
The study S47 identifies OSS evaluation models for selection and adoption, assign different weights to different factors. The study S49 identifies twenty-two adoption factors. The research in the study shows that OSS adoption is attracting research. The significant success factors for OSS development discusssed by S55 are also included in the sub-category "*OSS Benefits/Drawbacks*" in the category of "*Conceptual*".

5) Performance Metrics:
Work published in the category of performance metrics has ten studies mapped to five sub-categories. No secondary work exists in the sub-category of software development and efficiencies of OSS code. This sub-category represents quality aspects related to the process and product of OSS development. Other sub-categories of software quality, especially testing and bug fixes, related to OSS security and OSS success have systematic secondary studies published in these areas are explained below.

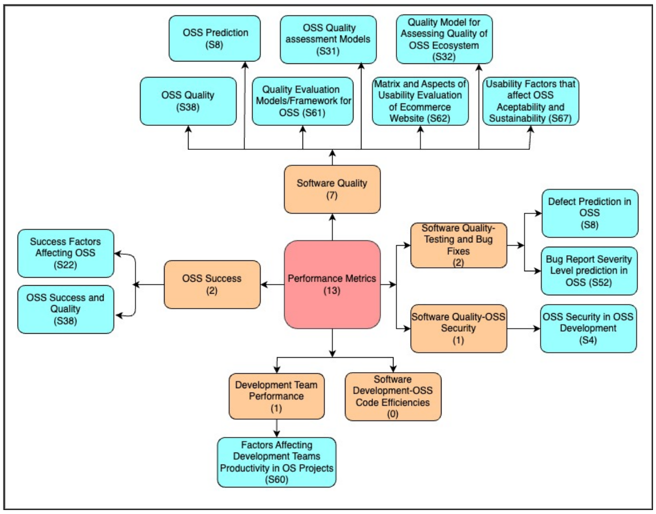

FIGURE 10: **Category: Performance Metrics**

a: Software Quality:
Seven studies S8, S31, S32, S38, S61, S62, and S67 discuss software quality aspects from different angles. The study S8 discusses software defect prediction. The study S31 highlights research on quality assessment, and also identifies quality assessment models. The study S32 identifies quality characteristics and their associated metrics for assessing quality. Another study S38 tries to find the relationship between OSS quality and success. The study S61 defines quality models such as ISO 9126 and ISO 25010 as well-designed and mature models that are adapted for commercial use, however not fit for evaluating an OSS.

b: Software Quality-Testing and Bug Fixes:

Two studies S8, and S52 discuss the testing, and bug-fixing aspect of quality. Study S8 focuses on defect prediction and is already defined in sub-category "*Software Quality*" in the category of "*Performance Metrics*", whereas, the study S52 is on bug severity.

c: OSS Success:

Two studies, S22, and S38 discuss OSS success factors and characterize them. The study S22 characterizes these factors from developer, product and user perspective. It also defines success indications.

d: Software Quality-OSS Security:

The study S4 discusses OSS security and identifies frequently addressed areas in OSS security.

e: Development Team Performance:

The study S60 discusses development team performance, and classifies factors that influence productivity.

6) Legal and Regulatory:

Two studies S45, and S40 are only published in the category of legal, and regulatory. No study is published on legal issues of OSS, and OSS intellectual property rights.

a: OSS Licensing:

The study S45 presents motivational factors for choosing an OSS license related to the user and developer motivation, also mapped to the sub-category "*User and Developer Motivation*" in the category of "*OSS Production*".

b: OSS Standards and Regulation:

The study S40 compares OSS and CSS certification already discussed in the sub-category "*OSS Vs Proprietary*" in the category of "*Conceptual*".

7) Beyond Software:

The last category, beyond software, has nine studies mapped to open paradigm and to open innovation. Other sub-categories do not have any study mapped to them. This is depicted in Figure 11.

a: Open Paradigm:

An interesting research area is that of Inner Source Software (ISS) development, discussed in the study S15. Two studies, S7, and S43 discuss the use of processes and practices of OSS by companies. The study S43 identifies that work is mostly done in the area of the theory of ISS, framework, and method for implementing the ISS approach. The study S26 researches another interesting and popular area of open design in many disciplines like design, engineering, computer science, social sciences, and management.

The study S54 focuses on the adoption and adaptation of different contexts and dynamics of the inner source community.

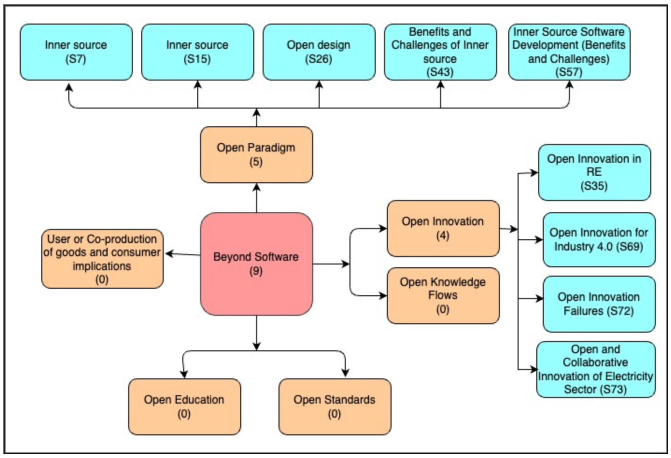

FIGURE 11: **Category: Beyond Software**

The research also highlights the challenges of inner source implementation.

b: Open Innovation:

The study S35 identifies research in the area of business models combining OSS and closed source development and crowd-sourcing, but states limited research is done on Open Innovation (OI) in Requirement Engineering (RE). The study S69 identifies themes in the area of open design in data science. Another study S72 discussing OI failures, shows an increase in research publications in the area. Finally, the study S73 discusses the use of OI in the electricity sector as part of energy transition and highlights the importance of partnerships with universities.

C. RESULTS RQ3: WHICH FUTURE RESEARCH DIRECTIONS ARE REPORTED IN THE SYSTEMATIC SECONDARY STUDIES ON OSS RESEARCH?

In this research question, we identify and categorize the future directions elicited in the systematic secondary studies on OSS using thematic analysis [8].

The future directions are extracted from the headings like discussion, summary, conclusion, future work, result, and analysis, etc. The themes and codes, identified, are also inspired by the "Software Engineering Body of Knowledge (SWEBOK) [1]".

The thematic analysis is initially conducted on the complete set (74 studies) of future directions, however, below, you will find the defined codes and themes extracted of studies published in years (2018-2022) outlining potential future research directions. The rationale behind focusing on the most recent future directions is to exclude those that may already have been addressed.

1) OSS Development Process:

The studies on the topic of the OSS development process, inner-source, OSS effort estimation, OSS maintenance effort estimation, and OSS knowledge management are discussed collectively as they are part of a process. There are six studies in this code that discuss future research.

OSS Process:

The study S48 (2020) identifies the need to understand the OSS development process in practical settings to mitigate OSS project failure. The recent studies S43 (2018), and S54 (2020) identify the need to conduct an in-depth analysis of the area and customize OSS practices according to the organizations by covering more databases for research and exploring ways to manage the inner source community effectively.

The study S66 (2022) defines the need for more comparative studies in the field of OSS maintenance effort estimation. The data pre-processing of repositories is needed to perform data mining, with more machine learning studies to evaluate the improvement in performance, and impact of estimation on performance. The study motivates to work on new perspectives of open-source maintenance effort estimation, such as man days. Another study S71 (2022), presents the need to ensure the comparability of results, by working on data pre-processing of data sources in a standard format. There is a need to investigate the new validation methods, such as "Cross Release Validation (CRV), Cross Project Validation (CPV), and Sliding Window (SW) for Open-Source Maintenance Effort Estimation (OMEE)". It motivates to estimate maintenance effort based on code source data sources and different types of metrics such as "code source metrics, bug fixes/resolution time prediction, etc.". The study also highlights the need for more studies to reduce the external and conclusion validity threats of empirical studies.

Knowledge Management:

The study S25 (2019) on knowledge management identifies knowledge retention in OSS projects, proactive measures in OSS to reduce knowledge loss, and knowledge management evaluation metrics in OSS projects as potential research areas.

2) OSS Contributors:

OSS contributors are OSS developers, OSS communities, OSS organizations. The code identifies five studies altogether.

OSS Developers:

The study S50 (2020) presents areas of joining, abandonment of newcomers to OSS communities and mentoring process, tool support for developers on-boarding, easy migration between communities, support for technical barriers, motivation, and retention of community members in a project as future research areas. Another area of research is OSS developers forking (where developers download code, adapt, and upload it back). The study S57 (2020), suggests looking into the forking of OSS developers, motivation, and consequences of using forking, etc. They identify the need to look into the prediction models for fork effectiveness. The study S58 (2020) proposes to investigate the sentiments of OSS projects that adopt frequent releases and their impact on software productivity. It also highlights the need to identify how programmer sentiments vary between releases. The study S63 (2022) highlights the need to measure the effectiveness of women's participation strategies by collecting metrics before, during, and after the implementation of the strategy. It motivates the researchers to explore why women leave OSS project, avoid participation in OSS, and do not join OSS projects. Investigation of participation of the minority population in OSS can also be a future work.

OSS Communities:

The study S50 (2020) defines future work in the area of "community dynamics, practices, and processes of community participation, researching the whole of the software ecosystem, project governance, and difficulties associated with finding a task and project characteristics". The study S67 (2021) emphasizes investigating communication and coordination between OSS members as part of community support, and determining the role of developers from different cultures and their manifestation.

3) OSS Evolution and Prediction:

The theme of OSS evolution, and prediction contains three systematic secondary studies.

Architectural degradation is part of OSS evolution. The study S46 (2020), defines future directions in this area as architecture erosion (on OSS or industrial system), architectural bad smells in combination, and metrics to be analyzed from other fields for detecting architecture-related smells. Work is required in "Adaptive Re-configurable Control Analysis, Design & Evaluation) ARCADE tools for architectural recovery, and architectural conformance studies" using different frameworks to identify critical and necessary architectural rules.

The study S52 (2019) identifies future research areas as improving the state-of-the-art of severity prediction algorithms by novel approaches for bug report handling, like machine learning algorithms, and to extend severity level prediction in FLOSS to a commercial level. There is a need to investigate data structures for storing the temporal evolution of bug reports and user experience during the prediction of bug reports. The study S65 (2021) identifies, that the temporal project information can be used via Social Network Analysis to determine the success of the OSS project and to understand OSS evolution.

4) Use of OSS in Different Domains:

OSS is applied in a variety of disciplines like education, medicine, etc. Three studies discuss the latest future work in these areas.

a: ***OSS in Education***

A recent study S59 (2019) stresses the need to cover more universities to understand students' perception of OSS literature and determine influencing factors for OSS organizations and communities' productivity.

b: ***OSS in Medicine***

The study S41 (2018) identifies the low level of adoption of modern ICT tools and infrastructure in the health industry and also immature OSS adoption in public administration. The study S64 (2022) in the area of OSS (ATs) defines the need to improve computer vision techniques and libraries. It also emphasizes establishing robustness and quality via trials with disabled people. Research can also propose improvements in ATs to make them feasible for low and medium-income countries. The designs of such initiatives should be published in specialized OSS hardware journals.

D. OSS ADOPTION, OSS ADAPTATION, AND OSS INTEGRATION:

The study S47 (2020) defines the need for a validated common model for OSS adoption. The study S49 (2020) identifies a lack of experience reports in the area of FLOSS adoption, and emphasizes the creation of guidelines for adopting FLOSS and its application in new domains.

1) OSS and Quality:

The study S38 (2019) identifies limited empirical studies and less number of studies on introducing OSS tools for the quality evaluation, and success of OSS, and wants future research to clarify terminology, define metrics, and develop tools for measuring quality and success. The study S61 (2022) presents future directions related to the need for robust studies in the field of OSS quality evaluation, keeping in view the needs of the OSS community. The community needs a common vocabulary, standardization, and guidance on OSS quality evaluation. Moreover, it highlights the need for metamodels for OSS quality specification and evaluation, and a need to evaluate quality during evolution as a result of changing developers who maintain the OSS.

2) OSS Selection and Evaluation:

The study S27 (2018) identifies the need to evaluate and improve the components of the OSS architecture and the need for tools, methods, and algorithms for GIS web architecture. The study S47 (2020) defines the need for a validated common model for OSS selection and evaluation. It also identifies the need for a tool that supports and simplifies the applicability of the proposed models for the assessment of OSS Products.

3) Usability in OSS:

The study S62 (2022) identifies the need to elaborate a new set of usability evaluation metrics for e-commerce websites based on open-source platforms. The study S67 (2019) identifies the need for more research on usability in OSS, i.e. more user research in OSS, more usability methods in OSS, participation of usability specialist in OSS communities and integrating exiting HCI and software philosophy in OSS.

4) Use of Open Innovation:

The study S69 (2022) emphasizes to identify the factors, solutions and actions to be implemented for open approaches to innovation and social sustainability. The study S72 (2022) identifies the need to extend the SLR by adding more keywords, publication sources, more databases and screening process to identify open innovation failures. The study S73 (2022) also defines the need to evaluate the statistics of private companies employing OSS, such as "locations, impact on social and financial performance" in energy sector. It also identifies the need to investigate how outbound innovation can impact pace of energy transition without affecting profit and business position. Furthermore, sharing of open technology developments and data with other actors should also be encouraged. The study also identifies the need to quantitatively evaluate the impact of open movement on "research development, digitization trends data privacy issues, and geographical uptake".

5) OSS Platforms, and Open IoT Platforms:

The study S56 (2020), suggests researching different open IoT platform types and dimensions.

6) Use of OSS CASE and Open-Source Business Intelligence (OSBI) Tools:

The study S17 (2019) identifies future work as strategies required for dealing with barriers preventing OSBI tool adoption in organizations, the use of different research methods to be implemented in the open-source business intelligence tools domain, and the inclusion of different area business intelligence experts in the survey.

7) OSS Interaction Design, and Open Design:

A recent study S26 (2019), highlights the need to explore, how to keep the design open.

V. DISCUSSION

To the best of our knowledge, and from the analysis of the literature, we can say that there is no tertiary study in the area of OSS and this is the first attempt to aggregate information present in SLRs and SMS in OSS. The review revealed that there are a lot of diverse systematic secondary studies in OSS. The categorization of knowledge areas and topics are based on an already published taxonomy [2]. The major differences between the taxonomy and this tertiary study are already discussed in Background and Related work II. However, the improvements suggested to OSS taxonomy are discussed below:

Suggested Improvements to OSS Taxonomy [2]

The taxonomy can be improved and enhanced in our opinion. The categories and sub-categories are at different levels of abstraction, e.g., the sub-category of "OSS research Categorization/Research Agenda" is a general sub-category including all OSS studies that have some form of categorization/state-of-the-art or framework, whereas the sub-categories of OSS License, OSS Adoption, OSS Quality include specific studies of these areas.

Some studies do not belong to any category of taxonomy, e.g., studies on OSS Platforms, and OSS Ecosystems. Moreover, OSS Adaptation/Customization is a prominent area of research but is not covered by any of the taxonomy category.

The main findings of the research are summarized according to the research questions and presented as such

A. RQ1: WHAT ARE THE CHARACTERISTICS OF SYSTEMATIC SECONDARY STUDIES ON OSS RESEARCH?

The results of RQ1 show the majority of the systematic secondary studies are published from Brazil, and no author has more than three secondary studies in the area of OSS. There is an increasing trend of systematic secondary studies in OSS research in the years "2020, 2022, 2019, 2016, and 2014". The years covered by the majority of the studies are from 2003 to 2016, and the highest covered year is 2010.

It is also seen that there is a need to improve the quality assessment and, synthesis of SLRs as most of the studies have not performed the synthesis and have a poor-quality assessment. This point is also emphasized by various other tertiary studies conducted in the general area of SE [22, 23, 10, 9, 25].

The synthesis of data is not performed in SMS, since the focus of SMS is not synthesizing data. However, nine SMS have scored "1" or "0.5" in synthesis. Quality assessment is a major step in SLRs, but twelve studies out of forty-nine have "0" score in the synthesis of quality assessment. This supports the confusion between SMS and SLR also identified and highlighted by [9].

SMS mostly does not perform the quality assessment, as only three studies out of twenty-five have scored "1" with "0" scores in the remaining studies. This finding is also supported by the study [29, 40].

SLRs are not excluded from the tertiary study due to low-quality scores, since the purpose of a tertiary study is to categorize and provide information on the research area. This finding is also supported by [6].

The main strategy used for systematic reviews is that of Kitchenham [20] for SLR, and Peterson for SMS [31, 20]. However the, "Need to establish review", explicitly mentioned in the guidelines [18], and an integral part of the planning phase is mostly not defined by the systematic secondary studies.

The criteria of inclusion/exclusion are explicitly mentioned in the majority (sixty-three out of seventy-four) of the studies. The search process is usually adequate and more than half of the studies, i.e. forty-six out of seventy-four have scored "1", whereas thirty-six studies have scored "0.5" which partially provide the search strategy. This finding is also supported by [19].

Most of the studies present descriptions of primary studies, thus scoring, "1" i.e., forty-nine out of seventy-four, whereas eighteen of the studies present summarized descriptions resulting in "0.5" score. Seven of the studies do not provide any kind of information related to the description of primary studies. This finding is also supported by [19].

B. RQ2: WHICH TOPICS ARE INVESTIGATED IN THE SYSTEMATIC SECONDARY STUDIES ON OSS RESEARCH, AND HOW CAN WE CLASSIFY THEM?

Mapping systematic secondary studies to taxonomy themes aided in assessing the volume of research in the OSS domain. The majority of SLRs and SMS in this tertiary study align predominantly with the "Categorization/Research Agenda theme". This theme encompasses studies involved in categorization and presenting the current state of various aspects within OSS research, since one of the primary objectives of SLRs and SMS is to categorize primary studies, thus majority of the studies fall in this category. Additionally, these same studies are cross-referenced with other relevant themes, such as "OSS Production", "OSS Applications", "OSS Diffusion", etc. Moreover, there is substantial research within the "OSS Production theme", covering topics like OSS developer motivation, OSS communities, OSS processes, and Community evolution, among others.

Themes with limited research include "Beyond OSS", "OSS Applications", "Performance Metrics", and "Legal and Regulatory". Therefore, researchers can explore secondary research on various topics, like OSS implementation, Legal issues, intellectual property rights, Open standards, Open education, and more. Likewise, within the "OSS Applications" theme, there is coverage in education, business, and medicine, but critical areas like cyber security, academic research, and natural sciences lack secondary research. The topics in "Beyond Software" that have SLRs and SMS are related to Open paradigm and Open innovation. Having secondary research in these areas shows the beginning of research on the use of OSS in areas such as corporate governance and innovation. Other codes like Open Knowledge Flows, Open Standards, Open Education etc. do not have any secondary research.

Detailed discussions on specific research areas that researchers can undertake are provided in the "Future Directions" and in the section "Implications of this Research for OSS Researchers".

C. RQ3: WHICH FUTURE RESEARCH DIRECTIONS ARE REPORTED IN THE SYSTEMATIC SECONDARY STUDIES ON OSS RESEARCH?

The potential future research areas in OSS identified by recent literature includes studies in the main themes of OSS contributors (eight studies), OSS development process (five studies), OSS evolution and OSS prediction (three studies), use of OSS in different domains (three studies), OSS adoption, adaptation, and integration (three studies). The rest of the themes have either two or one study discussing future directions.

- Concerning the future directions in the OSS developers sub-area under OSS contributors, the participation, attraction, retention, migration, and onboarding of OSS developers in the OSS community requires research. There is a need to work on the barriers that are faced by newcomers, strategies to minimize these barriers, metrics to grade the barriers, and the impact of barriers on the quality of contribution.
- Furthermore, developers forking motivation and consequences of using forking, prediction models for fork effectiveness need to be seen.
- Research is needed in the area of community dynamics, practices, and processes of community participation, and to investigate communication and coordination between OSS members as part of community support, and determine the role of developers.
- The area of the OSS development process requires evaluation of the OSS process in practical settings along with its customization according to the organization. There is also a need to manage the inner source community effectively. The process of maintenance effort estimation requires further research. Another area for research in the OSS process is knowledge management.
- The area of OSS evolution needs further research in the sub-areas of OSS evolution process, evolution prediction, community evolution, bug prediction, and architectural degradation of OSS. Furthermore, social network analysis can be used to determine the success of the OSS project and understand evolution.
- In the domain of OSS education, there is a need to understand students' perceptions of OSS literature and determine influencing factors for OSS organizations and communities' productivity. In the domain of OSS in medicine, there is a need to improve the quality of techniques and the robustness of the methods.
- In the area of OSS and quality, tools, and models are required for OSS quality evaluation.
- In OSS adoption, there is a need to research guidelines of OSS adoption and its application in new domains with tool support.

D. IMPLICATIONS OF THE RESEARCH FOR OSS PRACTITIONERS

The section details the implication of the research for OSS practitioners.

Implication for OSS practitioners

Categorizing OSS research proves advantageous for OSS practitioners as it offers practical solutions, effective strategies, best practices, and valuable information to facilitate well-informed decision-making. Frameworks and models (S7, S41, S47) designed to assist organizations in adopting OSS are systematically organized for practitioners' reference. Likewise, factors crucial for the success of OSS adoption (S49, S55) should be carefully assessed in the adoption process. Intrinsic motivational factors and information pertaining to OSS selection (S45, S47) contribute to sound decision-making practices. OSS success factors from user, product, and developer perspectives (S22) serve as valuable insights for practitioners.

OSS practitioners can mitigate the causes of architecture erosion (S49) and monitor associated indicators. Solutions addressing architectural degradation (S46) can be implemented to enhance and improve architectural structures. Methods, tools, and techniques for interaction design (S2) are available for OSS practitioners. Practitioners improve usability of sustainable OSS (S67).

Addressing knowledge problems (S4), implementing strategies for knowledge retention and sharing during OSS development (S25), and utilizing metrics for evolution prediction (S29, S39) are key aspects that OSS practitioners can focus on for effective maintenance.

Practitioners in the OSS realm can effectively plan maintenance through bug report severity prediction (S52) and utilize various methods and techniques (S66, S71) for estimating maintenance efforts. Quality assessment and evaluation models and frameworks (S31, S61) can aid in evaluating the quality of OSS. Strategies for implementing rapid releases in OSS (S28) are available for adoption by OSS practitioners.

Implication of Research for Community Leaders/Coordinators

For community leaders and coordinators, responsible for fostering collaboration and inclusion in the OSS community, the findings of this research are valuable. Barriers faced by newcomers (S9) can inform efforts to enhance inclusivity, while research (S53, S63, S70) provides strategies for ensuring women's participation in OSS communities. Insights into attracting developers (S15) and motivating programmers and scientists (S18, S44) to contribute to OSS can guide community leaders and coordinators. Understanding power distribution (S70) enables community members to make decisions aligned with objectives.

Implication of Research for Computing Faculty

In educational settings, computing faculty can leverage research findings (S21, S51) to comprehend challenges in using OSS in education, striving to reduce obstacles for an effective learning experience.

Implication of Research for Software Organizations

Software development organizations can benefit from this research (S43) by understanding challenges related to Inner Source Software (ISS). Research on reconciling software development models (S23) offers approaches and strategies for plan-driven, agile, and OSS reconciliation, while business models for commercial OSS (S15, S24) provide insights for software organizations.

Implication of Research for Diverse Organizations and Domains

Diverse organizations can make informed decisions (S7) by understanding the advantages/disadvantages of using OSS. The applications of OSS in various domains like automotive and medical (S5) can guide practitioners in those fields. Research on OS Electronic Health Record (EHR) systems (S34), OSS model applications for the drug discovery industry, and the use of OSS in Assistive Technologies (AT) (S64) offer domain-specific benefits. For those dealing with Graphical Information Systems (GIS), architectures integrating open-source components (S27) can be identified. Furthermore, industry users can benefit from detailed processes for selecting off-the-shelf components (OTS) (S15), and Open-Source Business Intelligence (OSBI) tools (S17) can find applications across various business contexts

E. IMPLICATIONS OF THE RESEARCH FOR OSS RESEARCHERS

Categorizing research in OSS serves to provide researchers with insights into the current state of knowledge and the breadth of available information. This tertiary study contributes to establishing a shared understanding within the OSS research community. It identifies gaps and highlights areas where further research is needed for maturity of OSS research. The conceptual category exhibits significant research focus on OSS adoption (S7, S8, S36, S41, S47, S49, S55, S63), indicating a saturation in this particular area. Conversely, domains where OSS is used, but has limited empirical research such as the application of OSS in dentistry (S30), Open innovation in requirement engineering (S32), use of OSS in Assistive Technologies (AT) (S64), work to reduce the complexity of configuring a user environment in the area of OSS in product development (S15) are good empirical research opportunities for OSS researchers.

The codes such as Individual and Team Learning, Team/Project Leadership, OSS Production-Role of Licensing and IP, Role of Volunteer Users/Developers, OSS Intellectual Property Rights, OSS Legal Issues, Software Development-OSS Code Efficiencies, OSS Descriptive etc. lack secondary research. Secondary research in these areas will aid in aggregating and categorizing related work, enhancing its comprehension and analysis.

Additionally, areas with limited primary studies like the use of OSS in Electronic Health Record Systems (EHRS) (S34), certification of OSS (S40), selection of OSS licenses (S45), usability evaluation of e-commerce websites based on OSS platforms (S62), and power relations within an OSS ecosystem (S70), offer potential for further exploration by OSS researchers. OSS researchers can advance the OSS field by addressing highlighted issues, challenges and risks, such as proposing solutions to barriers faced by newcomers (S9), strategies to mitigate knowledge loss problems in OSS communities (S25), work on minimizing/removing risk and barriers of OSS adoption (S14, S36, S41), improving factors impacting developers' productivity (S60), strategies to address challenges in using OSS in Computer Science (CS) education (S21, S51), resolving key issues of certification for quality assurance (S40), addressing challenges in reconciling plan-driven, agile, and OSS development methods for effective development (S23), overcoming business challenges related to OSS (S15), proposing solutions to challenges in inner source software development (S43), solutions to avoid failures in open innovation (S72), work to reduce the causes of architectural degradation (S49), strategies to mature the open-source component market (S15), empirically validation of the strategies to overcome the challenges face by women to participate in OSS communities (S63, S70), and reduce the challenges of Inner Source Implementation (S53).

VI. THREATS TO VALIDITY

We followed the guidelines of kitchenham [24] for performing the systematic literature reviews, this tertiary study is a systematic review of the systematic secondary studies on open-source research. Therefore, we followed the classification proposed by Ampatzoglou et al. [3] for reporting the threats to validity and corresponding mitigation actions for secondary studies in software engineering. The study classifies the threats to validity into three categories: "study selection validity, data validity, and research validity". Each of the categories with its mitigation strategy is defined below:

A. STUDY SELECTION VALIDITY

Study selection validity relates to threats of the search and selection phase. We took the following mitigation steps to reduce study selection threats:

- The search string is constructed systematically, by identifying keywords of OSS from systematic secondary studies and keywords of "SLR and SMS" from the tertiary studies. These are then analyzed to remove redundant, and irrelevant keywords. The final search string is constructed after piloting the initial string, ensuring correctness and coverage.
- The search string is executed on all the related and famous CS, and SE databases to ensure maximum

retrieval of relevant published material. Moreover, the same databases are used by similar studies. The databases searched are (IEEE, ACM Digital Library, Scopus, Springer Link, and Science Direct).
- Quasi Gold Standard (QGS) is used to ensure that all the relevant studies are retrieved from the selected databases. The sensitivity value is 76.4% and the precision is 20.96 %, which falls in the accepted criteria range by QGS.
- Forward and backward snowballing, also known as citation snowballing [24] is performed to reduce the risk of missing important evidence. Six more systematic secondary studies are identified from the snowballing phase.
- The inclusion and exclusion phase is based on an explicitly designed criterion that is also pilot-tested. The criterion is defined keeping in view the scope of the tertiary study. Moreover, the inaccessible papers are requested from contacts, as a result, only two papers are excluded which are finally unavailable.
- Zotero is used to automatically remove duplicate studies. The studies after automatic scanning are manually scanned to remove the remaining duplicates.
- The search strategy explicitly excludes the grey literature, as it is not aligned with our study goals. This study is a tertiary study that only includes systematic secondary studies published in the OSS research area. Therefore, some of the related surveys and reviews may be missed due to the nature of the study.
- The first and second authors performed inclusion/exclusion at level 1 separately, and inclusion/exclusion was also performed on a 10% random sample by the fourth author to ensure reliability. The second author also performed inclusion/exclusion at level 2 on a random sample of 10%, where the conflicts between the two authors are documented and resolved in a meeting between the first and third authors. Reliability is ensured by the same task being performed by more than one author to reduce researcher bias. The kappa statistics are also calculated as 85.39% in level 1 which is a very good inter-reviewer agreement percentage.

B. DATA VALIDITY

Data validity relates to threats encountered during data extraction and analysis. The data validity is ensured with the help of the following steps:

- The data extraction form is designed, to keep in view the research questions. The data extraction form is piloted, and the extracted data is discussed among the first, second, and third authors. The form is refined as a result of the piloting phase. The finalized data extraction form is used to save data.
- The quality assessment of the selected studies is performed using the DARE criteria. The quality score is commonly used [37] is also used for this tertiary study.
- The first author performed data extraction and quality assessment on the complete data set, whereas the second author performed these steps on a 10% random sample. The disagreements are discussed and resolved in a meeting between the corresponding authors. Doing so helped to remove the researcher's bias and helped increase the reliability of the study.
- The extracted data is mapped to the already defined OSS taxonomy of Aksulu and Wade [2]. The mapping is done by the first author and validated by the second author on a 10% random sample to remove researcher bias. The conflicts are minimal, that are discussed in the meeting with the third and fourth authors to reach a consensus and achieve accurate mapping to OSS taxonomy.
- The future directions are thematically analyzed [8] by the first author and validated by the second author on a 10% random sample. The differences are minimal and are resolved with discussion.

C. RESEARCH VALIDITY

Research validity relates to the overall threats to the research design like generalizability, coverage, etc. Research validity is ensured by the following mitigation steps:

- The guidelines of [20, 21] are followed to design a protocol and the tertiary study is executed according to the protocol.
- To remove the researcher bias, all the steps of search, study selection, data extraction, and quality assessment are performed either by multiple researchers or by one researcher with another validating it on a random sample.
- The extracted data and its mapping are available online.
- In case of disagreements and conflicts between the researchers at any step of the protocol, a meeting is arranged between the corresponding researchers, and conflicts are resolved.

VII. CONCLUSION

The tertiary study categorizes areas, and topics of systematic secondary studies in OSS research, based on the taxonomy of Aksulu and Wade [2].

The study highlights major work in the category of "***Conceptual***" and "***OSS production***". The "***conceptual***" category has most of the work in the sub-category of "*OSS Categorization/Research Agenda*" (forty-seven studies), followed by "*OSS Vs Proprietary*" (eight studies), "*Business/Economic Models*", "*Strategies/Policies of OSS*" (five studies), and "*OSS benefits/drawbacks*" (four studies). The second category "***Performance Metrics***" has seven studies mapped to it in the sub-category of "*OSS Quality*". Next, category "***OSS Production***" has ten studies in "*Communities*", nine studies on "*user and developer motivations*", and eight studies in "*OSS Process*". The area of "*Community and Evolution*" has six studies mapped to it. The area of "*Education*" in the

"***OSS applications***" category has five studies. Furthermore, the area of "*OSS adoption*" and "*OSS adoption factors*" both in "***OSS Diffusion***" category has five studies, and finally, "*Open Paradigm*" in "***Beyond Software***" category also has five studies.

This tertiary study also does the quality assessment of the included systematic secondary studies and finds that the majority of the studies lack quality assessment and synthesis. There is a need to focus on these two by the SLRs. It is also seen that there is confusion between SMS, SLR, as some SLRs have done only mapping whereas, a few SMS are detailed enough to be SLRs. Thus, it highlights the need to work on the quality of SMSs and SLRs undertaken in OSS research.

The majority of the systematic secondary studies are published by Brazil, with Sweden, Finland, and Spain also, actively involved in OSS research. The publishing of systematic secondary studies increased in the year 2014 and between (2016, and 2022, excluding 2021).

The future directions highlighted identify a lot of research potential in the main areas of "OSS Contributors", "OSS Development Process", "Use of OSS in Different Domains", "OSS Evolution and Prediction", and "OSS Adoption, Adaptation, Integration".

The key areas within OSS research serve to update researchers on the current state-of-the-art, aiding them in defining a starting point for their research. This study identifies multiple future directions through which OSS research can be expanded.

The taxonomy categories, that have limited or no studies, indicate a necessity for further exploration in this domain.

Professionals in the OSS industry can gain insights into gaps and prospects within the field, allowing for well-informed decision-making. The technologies, tools, and techniques identified in this study, that need future exploration, can serve as a foundation for OSS industry practitioners seeking to progress in this field.

This tertiary study is the first step toward identifying and categorizing state of the art of OSS Research. In the future, we can use this to categorize and build a comprehensive taxonomy and framework for a deeper understanding of the area.

VIII. COMPETING INTEREST STATEMENT

There is no competing interest to be declared.

IX. AUTHOR CONTRIBUTIONS

Saima Imtiaz: Conceptualization, Methodology, Validation, Formal Analysis, Investigation, Data Curation, Writing Original Draft, Visualization, Project Administration

Salma Imtiaz: Formal Analysis, Writing, Review and Editing, Validation and Investigation.

Ahmad Almadhor: Review, Editing, Validation
Rastislav Kulhánek: Review, Editing, Validation

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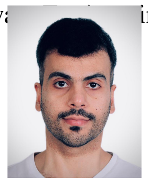

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References

[1] Alain Abran et al. “Swebok”. In: *Guide to the Software Engineering Body of Knowledge* (2004).

[2] Altay Aksulu and Michael Wade. “A Comprehensive Review and Synthesis of Open Source Research.” In: *Journal of the Association for Information Systems* 11.11 (2010).

[3] Apostolos Ampatzoglou et al. “Guidelines for managing threats to validity of secondary studies in software engineering”. In: *Contemporary Empirical Methods in Software Engineering*. Springer, 2020, pp. 415–441.

[4] David Budgen et al. “Reporting systematic reviews: Some lessons from a tertiary study”. In: *Information and Software Technology* 95 (2018), pp. 62–74.

[5] *Centre for Reviews and Dissemination, Systematic Reviews 2009*. https://www.crd.york.ac.uk/CRDWeb/AboutPage.asp. online;accessed 3 february 2022.

[6] Dolors Costal et al. “How Tertiary Studies perform Quality Assessment of Secondary Studies in Software Engineering”. In: *arXiv preprint arXiv:2110.03820* (2021).

[7] Kevin Crowston et al. “Free/Libre open-source software development: What we know and what we do not know”. In: *ACM Computing Surveys (CSUR)* 44.2 (2008), pp. 1–35.

[8] Daniela S Cruzes and Tore Dyba. “Recommended steps for thematic synthesis in software engineering”. In: *2011 international symposium on empirical software engineering and measurement*. IEEE. 2011, pp. 275–284.

[9] Daniela S Cruzes and Tore Dybå. “Research synthesis in software engineering: A tertiary study”. In: *Information and Software Technology* 53.5 (2011), pp. 440–455.

[10] Fabio QB Da Silva et al. “Six years of systematic literature reviews in software engineering: An updated tertiary study”. In: *Information and Software Technology* 53.9 (2011), pp. 899–913.

[11] Felipe Fronchetti et al. “What attracts newcomers to onboard on oss projects? tl; dr: Popularity”. In: *IFIP International Conference on Open Source Systems*. Springer. 2019, pp. 91–103.

[12] Bahar Gezici et al. “Quality and Success in Open Source Software: A Systematic Mapping”. In: *2019 45th Euromicro Conference on Software Engineering and Advanced Applications (SEAA)*. IEEE. 2019, pp. 363–370.

[13] Ronald L Goldman. “The reliability of peer assessments of quality of care”. In: *Jama* 267.7 (1992), pp. 958–960.

[14] Øyvind Hauge, Claudia Ayala, and Reidar Conradi. “Adoption of open source software in software-intensive organizations–A systematic literature review”. In: *Information and Software Technology* 52.11 (2010), pp. 1133–1154.

[15] Rashina Hoda et al. “Systematic literature reviews in agile software development: A tertiary study”. In: *Information and software technology* 85 (2017), pp. 60–70.

[16] Meng Huang, Liguang Yang, and Ye Yang. “A development process for building OSS-based applications”. In: *Software Process Workshop*. Springer. 2005, pp. 122–135.

[17] Giuseppe Iaffaldano et al. “Why do developers take breaks from contributing to OSS projects? A preliminary analysis”. In: *arXiv preprint arXiv:1903.09528* (2019).

[18] Staffs Keele et al. *Guidelines for performing systematic literature reviews in software engineering*. Tech. rep. Citeseer, 2007.

[19] Muhammad Uzair Khan et al. “Landscaping systematic mapping studies in software engineering: A tertiary study”. In: *Journal of Systems and Software* 149 (2019), pp. 396–436.

[20] Barbara Kitchenham. “Procedures for performing systematic reviews”. In: *Keele, UK, Keele University* 33.2004 (2004), pp. 1–26.

[21] Barbara Kitchenham and Stuart Charters. “Guidelines for performing systematic literature reviews in software engineering”. In: (2007).

[22] Barbara Kitchenham et al. “Systematic literature reviews in software engineering–a systematic literature review”. In: *Information and software technology* 51.1 (2009), pp. 7–15.

[23] Barbara Kitchenham et al. “Systematic literature reviews in software engineering–a tertiary study”. In: *Information and software technology* 52.8 (2010), pp. 792–805.

[24] Barbara Ann Kitchenham, David Budgen, and Pearl Brereton. *Evidence-based software engineering and systematic reviews*. Vol. 4. CRC press, 2015.

[25] C Marimuthu and K Chandrasekaran. “Systematic studies in software product lines: A tertiary study”. In: *Proceedings of the 21st International Systems and Software Product Line Conference-Volume A*. 2017, pp. 143–152.

[26] Anna Beatriz Marques, Rosiane Rodrigues, and Tayana Conte. “Systematic literature reviews in distributed software development: A tertiary study”. In: *2012 IEEE Seventh International Conference on Global Software Engineering*. IEEE. 2012, pp. 134–143.

[27] Carl-Eric Mols et al. “Principles for industrial open source”. In: *Self-published under CC* 4 (2018).

[28] Fabio Mulazzani et al. “Building knowledge in open source software research in six years of conferences”. In: *IFIP International Conference on Open Source Systems*. Springer. 2011, pp. 123–141.

[29] Bianca Napoleão et al. “Practical similarities and differences between Systematic Literature Reviews and

Systematic Mappings: a tertiary study." In: *SEKE*. 2017, pp. 85–90.

[30] Bianca M Napoleão, Fabio Petrillo, and Sylvain Hallé. "Open Source Software Development Process: A Systematic Review". In: *2020 IEEE 24th International Enterprise Distributed Object Computing Conference (EDOC)*. IEEE. 2020, pp. 135–144.

[31] Kai Petersen, Sairam Vakkalanka, and Ludwik Kuzniarz. "Guidelines for conducting systematic mapping studies in software engineering: An update". In: *Information and Software Technology* 64 (2015), pp. 1–18.

[32] Gery W Ryan and H Russell Bernard. "Techniques to identify themes". In: *Field methods* 15.1 (2003), pp. 85–109.

[33] Nicolás Serrano and JM Sarriei. "Open source software ERPs: a new alternative for an old need". In: *IEEE software* 23.3 (2006), pp. 94–97.

[34] Igor Steinmacher et al. "A systematic literature review on the barriers faced by newcomers to open source software projects". In: *Information and Software Technology* 59 (2015), pp. 67–85.

[35] Klaas-Jan Stol and Muhammad Ali Babar. "Reporting empirical research in open source software: the state of practice". In: *IFIP International Conference on Open Source Systems*. Springer. 2009, pp. 156–169.

[36] Rosemarie Streeton, Mary Cooke, and Jackie Campbell. "Researching the researchers: using a snowballing technique". In: *Nurse researcher* 12.1 (2004), pp. 35–47.

[37] June M Verner et al. "Systematic literature reviews in global software development: a tertiary study". In: *16th International Conference on Evaluation & Assessment in Software Engineering (EASE 2012)*. IET. 2012, pp. 2–11.

[38] Jane Webster and Richard T Watson. "Analyzing the past to prepare for the future: Writing a literature review". In: *MIS quarterly* (2002), pp. xiii–xxiii.

[39] He Zhang, Muhammad Ali Babar, and Paolo Tell. "Identifying relevant studies in software engineering". In: *Information and Software Technology* 53.6 (2011), pp. 625–637.

[40] You Zhou et al. "Quality assessment of systematic reviews in software engineering: A tertiary study". In: *Proceedings of the 19th international conference on evaluation and assessment in software engineering*. 2015, pp. 1–14.