A systematic mapping study of developer social network research

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Abstract
Developer social networks (DSNs) are a tool for the analysis of community structures and collaborations between developers in software projects and software ecosystems. Within this paper, we present the results of a systematic mapping study on the use of DSNs in software engineering research. We identified 194 primary studies on DSNs. We mapped the primary studies to research directions, collected information about the data sources and the size of the studies, and conducted a bibliometric assessment. Moreover, we determined open issues in the state of the art that can help to guide future research.

Keywords: developer social networks; mapping study; literature survey

1. Introduction

Social structures within software development projects are a topic that received a lot of attention in different research communities, e.g., by researchers interested in open source development, global software engineering, and mining software repositories. Developer Social Networks (DSNs) are often inferred automatically from information that can be found in forges like GitHub, Mailing Lists (MLs), Issue Tracking Systems (ITSs), and Version Control Systems (VCSs) of software development projects. The DSNs give valuable insights into the projects, e.g., regarding the importance of individuals, patterns in communication behavior, or for the identification of single points of failure. This article describes a mapping study performed based on the rigorous guidelines by Kitchenham and Charters \cite{Kitchenham:2007} for literature reviews with the goal to identify and map research on DSNs. We map the publications on DSNs published until 2017 to research topics and analyze the scope of the publications in terms of data sources, number of projects, and number of people. With our mapping study, we provide the following contributions.

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A contemporary overview of the state of the art of the literature on DSNs.

A summary of the already investigated research directions, including the relevant literature.

A summary of the data sources, as well as the size of the DSNs in terms of number of projects and people involved.

A bibliometric assessment to identify influential publications, authors, venues, and interest in the topic over time.

The identification of open issues within the current state of the art.

The remainder of this paper is organized as follows. We give a definition of DSNs in Section 2. In Section 3, we present our methodology for the mapping study, including our research questions, inclusion and exclusion criteria for the literature, how we identified publications, and the data we collected for each included publication. In Section 4, we give the results of our review, by listing the primary studies we found and map them to DSN concepts according to our research questions. In Section 5, we discuss open issues regarding DSN research based on the results of our mapping study. Then, we discuss related prior literature studies in Section 6, and conclude the article in Section 7.

2. Definition of Developer Social Networks (DSNs)

A definition is difficult, because different data sources, research goals, and modelling approaches are used to represent DSNs in the literature. Due to this, publications on DSNs contain the specific definition of their DSN structure, but this varies between publications. For our purpose, we require a definition, that can be applied to validate if a construct is an instance of a DSN. We identified three necessary and sufficient conditions for DSNs.

1. A DSN is described by a graph $G = (V, E)$ where $V$ denotes a set of vertices and $E$ a set of edges such that $E \subseteq V \times V$. The graph can be directed or undirected, depending on the intent of the researchers and the data that is used for modelling the DSN.

2. The vertices or a subset of the vertices must represent actors of a software development process, e.g., developers, users, or project managers.

3. The edges represent connections between vertices that are based on communication behavior (e.g., email communication) or collaboration behavior (e.g., contributions to the same software artifact).

An example of a DSN is given in Figure 1. This figure depicts an anonymized excerpt of the DSN created by Bird et al. [10]. The vertices in this graph represent different developers, which were active on Apache email lists. A directed edge between two vertices exists, if the developer has sent or replied to at least 150 emails of another developer.
3. Methodology

Our review follows the guidelines for systematic literature reviews proposed by Kitchenham and Charters [1]. Additionally, we used backward and forward snowballing, which was suggested for systematic literature studies by Wohlin [2]. In the following, we define our underlying research questions, inclusion and exclusion criteria, how we identified papers, and which data was collected for our study. We do not define our study as systematic literature review but as a systematic mapping study, because we did not perform any synthesis of the results, but only provide an overview of the literature.

3.1. Research Questions

In order to study the state of the art in DSNs, we defined the following five research questions to guide our mapping study. The first three research questions guide our analysis of the state of the art on DSNs. The fourth and fifth question give us insights into the community of DSNs research itself.

- **RQ1.** What software engineering topics have been addressed by DSNs?
- **RQ2.** Which data sources are used for modelling of DSNs?
- **RQ3.** What is the scope of the analysis...
  a) with respect to number of projects considered
  b) and people modelled by the DSNs?
- **RQ4.** What are the most influential...
  a) publications?
  b) authors?
  c) venues?
- **RQ5.** How did the interest in DSN research evolve over time?
3.2. Inclusion and Exclusion Criteria
To identify which papers should be part of our review, we defined the following criteria for inclusion:

• publications that describe DSN;
• publications that describe how DSNs may be created; and
• publications that describe theoretical aspects of DSNs.

Additionally, we used the following exclusion criteria:

• publications that only summarize existing work without new contributions;
• publications that only consider social networks or graph structures in general, without a direct and specific relation to software development;
• publications that were not peer-reviewed;
• publications that are not published in English; and
• publications that were first published after 2017-12-31.

3.3. Identification of Primary Studies
Figure 2 summarizes our workflow for the identification of primary studies. We used a five step procedure.

1. Initial scan of the literature using search engines and prior literature studies to identify a seed of publications.
2. Backward and forward snowballing of publications found in the initial scan.
3. Second scan of the literature using search engines to capture the remainder of 2017 and to account for delayed indexing of publications.
4. Backward and forward snowballing of publications found in the second scan.
5. Final check of inclusion and exclusion criteria on all identified publications.

In the first step, we searched for publications by using five search engines: Google Scholar, IEEE Xplore, ACM Digital Library, Springer Link, and Elsevier Search. We used three queries for each search engine: "developer social networks", "developer network", and "collaborative networks OSS". Table 1 gives an overview on the number of hits we had with our search terms in each of the search engines. This initial search was conducted between May 2017 and September 2017. Due to the extremely high number of hits, we considered only 750 hits per search engine and search term to get the literature seed for our mapping study. Next, we selected candidates for inclusion by reading the titles, abstracts, and, if it was necessary, the introduction and conclusion sections of the publications. We identified 145 publications through this procedure from the
search engines. Additionally, we scanned the primary studies from prior related literature studies by Zhang et al. [3], Tamburri et al. [4], Manteli et al. [5], and Abufouda and Abukwaik [6] (see Section 6). We identified 39 additional publications from the prior studies. This difference is mainly due to the scope of the other literature studies, especially with respect to search terms. For example, Manteli et al. [5] focus on global software engineering and, therefore, also use search terms that do not mention DSNs. Thus, we identified 184 publications in this first step.

In the second step, we checked the related work cited in each of the publications we found using the search engines. This step is also known as backward snowballing [2]. Moreover, we used the “cited by” function of Google Scholar, to identify publications that cited the publications we identified with the search engines. This step is also known as forward snowballing [2]. We also applied the snowballing to each additional publication we found. We identified 32 additional publications, i.e., 216 publications in total. The snowballing also served
to mitigate potential negative effects because we did not consider every hit for the search terms with the search engines. Our assumption is that we find the literature we may have missed through the snowballing. Moreover, same as the use of the prior literature reviews as seed for the snowballing, the snowballing allowed us to identify literature that did not mention the DSN in the paper title or abstract and was, therefore, missed by our search.

In the third step, we repeated our search for literature from the first step. This was required, because the initial search already started in May 2017, i.e., we could not be confident that all papers from 2016 were indexed by the search engines and part of the data for 2017 was not available yet. Thus, we repeated the search in July 2018. This way, we identified 13 new publications from the years 2016 and 2017, bringing our total number of publications to 229.

Afterwards, in the fourth step, we performed an additional round of snowballing on these additional 13 publications, but did not find any additional publications.

Before we started with the data collection, we validated whether all identified candidates met the inclusion criteria or violate the exclusion criteria in our last step. This way, we excluded 35 of the identified publications, mainly because they were not peer reviewed (e.g., book chapters), summarized only existing work (e.g., surveys, dissertation summaries), or because they did not contain anything specific to developer social networks, regardless of our initial assessment. This left us with 194 primary studies.

3.4. Data Collection

Once all literature was identified, we proceeded with the collection of the data required to answer our research questions. For RQ1, we first extracted the research questions and/or hypothesis that were formulated to guide the research, as well as the contributions as listed in the introduction or summarized in the abstract from the publications. We used inductive coding [7] performed by two researchers to identify the research topics of the papers from the hypothesis and contributions in order to obtain the necessary information to answer RQ1. For this, we printed the title, research questions/hypotheses, and contributions of each publication on a separate sheet of paper and sorted them incrementally by their topic, starting with a coarse-grained separation until we were satisfied that our categories provided a sufficient amount of detail for our mapping study. For RQ2 and RQ3, we extracted the data source, the number of projects, and the number of participants in the DSN used within the publications. For RQ4 and RQ5, we collected meta data about the publications themselves, i.e., the title, authors, publication venue, year, and number of citations. We organized the collected data in a spreadsheet which is made available as supplementary material.

4. Literature Review

In this section, we provide the review of the the state of the art of DSN research based on the data collection we described in Section 3. We systemat-
ically address different topics. We use the data from this review to answer our research questions in Section 5.

4.1. Research Directions

Based on the description of the contributions, the research questions, and the research hypotheses of publications, we identified seven general research directions regarding DSNs. For four of the general research directions we identified subtopics, i.e., specific aspects that were considered within the general direction. Table 2 shows our mapping of publications to the research directions including subtopics.

Nearly half of the publications we identified analyze the community structures in software development projects. Most of these publications analyzed the general structure of the DSN. However, we also identified five more specific subtopics of the analysis of community structures: the evolution of the communities by considering DSNs over time; community structures in the context of global software engineering; the formation of teams within development projects; the correlation between the community structure and code quality; and the analysis of socio-technical congruence.

DSNs are frequently used for the creation or improvement of prediction models for various aspects in software development projects. We identified six subtopics of prediction approaches using DSNs: defect prediction, i.e., using the social structure of a project to enhance models that estimate the defect-proneness of different parts of software; bug triage, i.e., support for assigning appropriate developers to work on bug reports; recommendation of suitable developers for project work in general; predictions of the outcome of a project, i.e., if projects are likely successful; predictions of build failures; and prediction of appropriate developers for code review.

The collaboration behavior was also scrutinized using DSNs. While DSNs are modelling some direct or indirect collaboration behavior in software development projects, the analysis of the collaboration behavior itself is in general not the focus. The publications we identified for this research direction focus directly on the collaboration behavior, e.g., which tools were used or how collaboration behavior was impacted by the structure of projects. In addition to research on collaboration behavior in general, we identified three more specific subtopics: collaboration behavior in global software engineering; problems in collaboration behavior and how they are reflected in DSNs; and collaboration between developers from different companies, including competitors in open source projects.

DSNs are also frequently used to assess the roles of developers within a development project, e.g., whether a developer is a core developer or a peripheral developer. While the identification of roles for developers in general is the main topic of this research direction, we also identified two other subtopics; the analysis of how onboarding of peripheral developers within projects works; and how developers specialize within a project.

We also identified research regarding tools for DSN analysis, mostly for the visualization of DSNs based on different information sources.
The validity of DSN research was also considered by five publications. These publications do not question the validity of DSN research in general, but rather analyze how properties of DSN research may depend on the specific context of research projects, e.g., the scope of the analysis or the repository that was used as source for the DSNs.

Finally, we found one publication on a data set that directly contains the graph structure of a DSN. The lack of publications on data sets shows that researchers either generate DSNs from data they collect, or from more general data sets that do not model DSNs directly. Such data sets contain general information mined from software repositories from which a DSN is then built.

| Category                        | #Pubs. | Publications |
|---------------------------------|--------|--------------|
| **Community Structure**         |        |              |
| General                         | 53     | [10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 31, 32, 33, 34, 35, 36, 37, 38, 39, 40, 41, 42, 43, 44, 45, 46, 47, 48, 49, 50, 51, 52, 53, 54, 55, 56, 57, 58, 59, 60, 61, 62, 63, 64, 65, 66, 67, 68, 69, 70, 71, 72, 73, 74, 75, 76, 77, 78, 79, 80, 81, 82, 83, 84, 85, 86, 87, 88, 89, 90, 91, 92, 93, 94, 95, 96, 97, 98, 99, 100, 101, 102, 123, 124, 125, 126, 127, 128, 129, 130, 131, 132, 133, 134, 135, 136, 137, 138, 139, 140, 141, 142, 143, 144, 145, 146, 147, 148, 149, 150, 151, 152, 153, 154, 155, 156, 157, 158, 159, 160, 161] |
| DSN Evolution                   | 14     | [63, 64, 65, 66, 67, 68, 69, 70, 71, 72, 73, 74, 75, 76, 63, 64, 65, 66, 67, 68, 69, 70, 71, 72, 73, 74, 75, 76] |
| Global SWE                      | 10     | [77, 78, 79, 80, 81, 82, 83, 84, 85, 86, 77, 78, 79, 80, 81, 82, 83, 84, 85, 86] |
| Team Formation                  | 6      | [87, 88, 89, 90, 91, 92, 87, 88, 89, 90, 91, 92] |
| Impact on Code Quality          | 5      | [93, 94, 95, 96, 97, 93, 94, 95, 96, 97] |
| Socio-technical Congruence      | 5      | [98, 99, 100, 101, 102, 98, 99, 100, 101, 102] |
| **Prediction**                  |        |              |
| Defect Prediction               | 11     | [103, 104, 105, 106, 107, 108, 109, 110, 111, 112, 113, 103, 104, 105, 106, 107, 108, 109, 110, 111, 112, 113] |
| Bug Triage                      | 9      | [114, 115, 116, 117, 118, 119, 120, 121, 122, 114, 115, 116, 117, 118, 119, 120, 121, 122] |
| Developers for Tasks in General| 4      | [123, 124, 125, 126, 123, 124, 125, 126] |
| Project Outcomes                | 3      | [127, 128, 129, 127, 128, 129] |
| Build Failures                  | 2      | [130, 131, 130, 131] |
| Developers for Code Review      | 1      | [132, 132] |
| **Collaboration Behavior**      |        |              |
| General                         | 11     | [133, 134, 135, 136, 137, 138, 139, 140, 141, 142, 143, 133, 134, 135, 136, 137, 138, 139, 140, 141, 142, 143] |
| Global SWE                      | 10     | [144, 145, 146, 147, 148, 149, 150, 151, 152, 153, 144, 145, 146, 147, 148, 149, 150, 151, 152, 153] |
| Problems                        | 7      | [154, 155, 156, 157, 158, 159, 160, 154, 155, 156, 157, 158, 159, 160] |
| Inter-company collaboration     | 1      | [161, 161] |
| **Developer Roles**             |        |              |
Table 2: Overview of the literature on DSNs by research directions.

| Identification  | 18 | 162| 163| 164| 165| 166| 167| 168| 169| 170| 171| 172| 173| 174| 175| 176| 177| 178| 179 |
|------------------|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|
| Onboarding       | 7  | 180| 181| 182| 183| 184| 185| 186| 187| 188| 189| 190| 191| 192| 193| 194| 195| 196| 197 |
| Specialization   | 1  | 187|
| Tools            | 10 | 188| 189| 190| 191| 192| 193| 194| 195| 196| 197| 198| 199| 200| 201| 202|
| DSN Validity     | 5  | 198| 199| 200| 201| 202|
| Datasets         | 1  | 203|

**Answer to RQ 1:** Community structures are the dominant research direction. Other frequently studied directions are DSNs for predictions, collaboration behavior and developer roles. Tools, studies on validity, and data sets play only a minor role.

4.2. **Data Sources**

There are five major data sources which are used by 184 of the 194 publications:

- Forges like GitHub or SourceForge that are used by millions of developers for hosting and developing open source software. These forges offer an integration of VCSs and ITSs within a single environment, often coupled with other services like Web pages, hosting of releases, or Wikis. Thus, they are a rich source for collaborations between developers, both within a project, as well as across multiple projects.

- ITSs like Jira or Bugzilla are used for the collection, tracking, and management of issues and work items within projects, e.g., change requests, bug reports, or questions by users. ITSs allow the discussion about issues, the definition of work flows for issues, and different types of resolutions.

- VCSs like Git or SVN are systems that track and archive changes of files and folders over time. Typically, VCSs allow different development branches and support working collaboratively on the same resources [8].

- MLs are collections of email addresses that can be used for communication within software projects. MLs may be restricted, e.g., not everybody may be allowed to post or subscribe to a ML. Participants of MLs may be natural persons (e.g., developers, users), but also systems (e.g., continuous integration systems, ITSs).

- Surveys, i.e., interviews or questionnaires that were used to directly ask developers about their communication behaviour within a development project.
In addition to the five major sources, there are other ways that researchers used to collect information about collaboration behavior which we summarized as "Other" in Table 3. These are IRC chats [79, 144, 201], plug-ins that monitor development environments [140, 158, 190], manual inspection of project documents, e.g., requirements [133, 146, 175], the web site Ohloh that provides statistics about open source development [31, 32], online discussion forums [56, 88], JAR files [108], the BlogLinks and Advogato social networks of software developers [53], on site researchers that observe communication behavior [159], and employee directories [156]. Additionally, one publication discusses DSNs from an abstract perspective and proposes the use of tracking for every communication including phone calls, emails, etc. [17].

Figure 3 depicts the number of data sources that were used for modelling DSNs. It highlights that 153 of the 194 publications build a DSN that is based on a single source, 34 publications used a combination of two data sources, six publications three data sources and one publication four data sources.

| Data Source | #Pubs. | Publications |
|-------------|-------|--------------|
| ITS         | 41    | 105, 116, 33, 113, 157, 158, 98, 127, 22, 165, 23, 100, 134, 52, 135, 136, 65, 96, 84, 117, 69, 171, 172, 139, 38, 150, 141, 72, 49, 113, 139, 137, 131, 114, 119, 61, 120, 121, 122, 186 |
| Forge       | 37    | 16, 18, 87, 21, 24, 123, 183, 25, 26, 89, 90, 29, 33, 132, 138, 170, 36, 125, 128, 41, 44, 193, 194, 17, 50, 126, 129, 91, 52, 202, 54, 132, 53, 59, 60, 75, 62 |

1The name has changed to https://www.openhub.net/.
2Both are not available online anymore.
Table 3: Data sources that were used for the modelling of the DSNs.

| Data Source            | Number of Publications |
|------------------------|------------------------|
| VCS                    | 32                     |
|                        | 104 95 181 189 99 167 154 28 |
|                        | 106 13 341 15 169 60 67 39 40 |
|                        | 203 103 42 198 109 97 110 176 |
|                        | 196 16 197 161 102 73 179 |
| ML                     | 22                     |
|                        | 77 10 19 11 183 27 124 12 68 |
|                        | 85 70 71 200 113 45 174 178 63 |
|                        | 71 160 162 134 |
| Survey                 | 11                     |
|                        | 78 145 81 83 173 37 174 149 85 |
|                        | 151 152 |
| Other                  | 10                     |
|                        | 17 188 144 159 190 31 32 108 |
|                        | 140 112 |
| ITS & VCS              | 13                     |
|                        | 199 155 94 106 164 107 63 100 |
|                        | 163 43 180 111 86 |
| ML & VCS               | 13                     |
|                        | 180 20 182 147 137 191 34 192 |
|                        | 92 48 101 143 70 |
| Survey & Other         | 3                      |
|                        | 146 135 175 |
| ML & Other             | 2                      |
|                        | 88 55 |
| Forge & Survey         | 1                      |
|                        | 80 |
| ITS & Survey           | 1                      |
|                        | 148 |
| ITS & ML               | 1                      |
|                        | 147 |
| ITS, ML & VCS          | 3                      |
|                        | 184 91 195 |
| ITS, ML & Other        | 1                      |
|                        | 56 |
| ITS, Survey & Other    | 1                      |
|                        | 79 |
| ITS, VCS & Other       | 1                      |
|                        | 136 |
| ITS, ML, VCS & Other   | 1                      |
|                        | 201 |

Answer to RQ 2: Software repositories like forges, ITSs, VCSs and MLs are the main sources for DSNs, however, surveys are also sometimes used. Publications commonly use a single source for DSN modelling. The knowledge about DSNs built with multiple sources is limited.

4.3. Number of Projects Analyzed

A major factor regarding the external validity of results is the number of projects for which data is collected. If only data about very few projects is used for an empirical study about a phenomenon that can be studied using DSNs, the results may not generalize to other projects. The likelihood that the results generalize to software engineering in general increases with the number of projects that are analyzed. Table 4 shows the number of projects per publication. The data we collected shows that most papers on DSNs perform some sort of empirical study to demonstrate their approach or research a phenomenon. Only 11 of the 194 publications we identified did not perform any empirical study. Moreover, we identified 9 publications for which we could not identify the number of projects from the publication. There were two reasons for this: either
Table 4: Number of projects that were analyzed as part of an empirical study of DSNs. Missing means that the number of projects is not or not accurately reported in the publication, NA means that the publication did not conduct an empirical study.

| #Projects | #Pubs. | Publications |
|-----------|--------|--------------|
| 1         | 65     | 105, 77, 78, 93, 10, 13, 82, 158, 144, 98, 127, 159 |
|           |        | 166, 63, 182, 82, 154, 28, 29, 65, 124, 31, 12, 69, 100 |
|           |        | 125, 171, 172, 139, 173, 37, 174, 187, 175, 103, 32 |
|           |        | 163, 43, 149, 109, 107, 60, 71, 150, 140, 110, 176, 45 |
|           |        | 195, 130, 72, 177, 111, 89, 49, 101, 52, 152, 153, 57 |
|           |        | 131, 114, 76, 121, 162 |
| 2-5       | 55     | 116, 155, 94, 115, 164, 157, 107, 180, 11, 104, 20, 29 |
|           |        | 95, 145, 88, 133, 190, 167, 134, 81, 183, 191, 27, 64 |
|           |        | 108, 117, 14, 33, 67, 68, 132, 138, 35, 36, 39, 40, 198 |
|           |        | 201, 13, 192, 91, 151, 196, 46, 92, 178, 73, 118, 112 |
|           |        | 56, 119, 179, 120, 122, 113 |
| 6-10      | 10     | 106, 154, 185, 108, 15, 169, 141, 201, 161, 186 |
| 11-100    | 16     | 199, 22, 80, 21, 137, 83, 96, 84, 66, 85, 48, 74, 133 |
| >100      | 28     | 14, 181, 21, 165, 23, 123, 135, 136, 89, 30, 32 |
|           |        | 170, 128, 88, 41, 14, 193, 47, 70, 120, 129, 51, 52 |
|           |        | 202, 142, 59, 60 |
| Missing   | 9      | 18, 146, 23, 138, 203, 54, 55, 68, 75 |
| NA        | 11     | 17, 156, 188, 189, 99, 147, 26, 33, 191, 197, 102 |

the authors did not report how they selected a smaller subset from a larger database or the authors did not specify which projects were used at all. This is not only problematic for evaluating the external validity of a study, but also hinders replications of the results. Of the 174 publications for which we could identify the number of projects, 65 used only a single project for their empirical study, 55 used only 2-5 projects for the empirical study. In other words, about 35% of the publications on DSNs used a single project, another 30% used 2-5 projects. Both numbers are extremely low and do not allow for a generalization of the findings. Another 10 publications only considered 6-10 projects, which is still a small number. On the bright side, 28 publications used more than 100 projects, i.e., larger sample sizes that usually allow to generalize findings. Still, these sample sizes regarding the number of projects pose a severe threat to the external validity of many empirical studies on DSNs. 21 of these publications use a forge as data source.

**Answer to RQ 3a:** Over 71% of all publications use less than 11 projects to evaluate their findings. Most publications with at least 100 projects use a forge as data source (21 of 28).
4.4. Number of Developers in the DSNs

The second major factor regarding the validity of results is the number of people that are part of the DSNs. Table 5 shows the data we collected regarding the number of people in the DSNs. In case a publication created multiple DSNs, e.g., one per project considered, we report the mean value of the people in the DSNs. The number of people modelled by the DSNs is relatively high. 53 publications have more than 1,000 people as part of their DSNs, 9 publications actually model more than 100,000 people. Only two publications have very small networks with less than or equal to 10 people, another 29 publications consider less than 100 people. Thus, for the publications for which the data about the number of people is available, the networks that are considered are in general relatively large. When we looked closely at the data, we observed two reasons for this: first, while many publications consider only few projects, these projects tend to be very large, e.g., Mozilla Firefox and the Eclipse IDE. Moreover, our data also shows that MLs and forges are the most common data sources for DSNs. Both capture not only developers, but also users of the respective projects. We also found a very concerning general trend in the literature: 47 of the 183 publications that performed an empirical study did not report the number of participants in the DSN. This is a vital piece of information for the estimation of both the internal and external validity of empirical studies that should always be reported.

Answer to RQ 3b: Most publications report networks that have more than 100 vertices. The number of developers is often much larger than the number of projects, because large-scale projects with big communities are analyzed.

4.5. Influential Publications

We collected data regarding the citation counts from Google Scholar. We take the pattern from the ACM Distinguished Paper awards to define our criterion for influential publications, and consider the top 10% with the most citations as influential. Since we have 194 publications, this means we consider the 19 publications with the most citations (Table 6). We note that the citations for the third most cited paper [10] also include the citations for the paper [19], because the two publications are considered as the same paper by Google Scholar. The 19 most influential publications address

- software development with globally distributed project members [148, 177];
- community structures in software development projects [10, 22, 182, 41, 11, 60];
- the formation of teams in projects through collaboration [90, 88];
- the identification of relationships between developers [156];
- the impact of coordination requirements between developers on tool design [158] and modularization [98];
Table 5: Number of people that are inside the DSNs. Missing means that the number of people is not or not accurately reported in the publication, NA means that the publication did not conduct an empirical study.

| #People | #Pubs. | Publications |
|---------|--------|--------------|
| 1-10    | 3      | 146, 146, 176 |
| 11-100  | 29     | 105, 77, 78, 116, 11, 127, 145, 88, 138, 166, 80, 83, 137, 168, 14, 67, 68, 37, 175, 163, 43, 149, 201, 85, 151, 16, 152, 179, 162 |
| 101-1000| 51     | 199, 87, 158, 144, 98, 23, 63, 107, 134, 182, 82, 184, 185, 27, 148, 121, 34, 115, 139, 63, 42, 138, 100, 171, 172, 139, 174, 40, 187, 103, 82, 198, 97, 71, 150, 141, 145, 196, 38, 80, 126, 202, 74, 153, 134, 114, 143, 61, 126, 70, 121 |
| 1001-   | 25     | 18, 137, 10, 19, 20, 183, 64, 29, 31, 117, 132, 36, 125, 173, 128, 70, 200, 13, 192, 47, 178, 49, 101, 53, 160 |
| 10000   | 19     | 164, 180, 123, 32, 63, 38, 41, 91, 195, 177, 50, 51, 52 |
| 100000  | 51     | 53, 73, 118, 119, 122, 186 |
| >100000 | 9      | 16, 155, 21, 25, 90, 65, 193, 60, 75 |
| Missing | 47     | 93, 94, 115, 106, 107, 104, 79, 95, 184, 22, 165, 159, 190, 24, 154, 135, 136, 191, 28, 89, 83, 96, 84, 50, 108, 85, 170, 89, 203, 44, 109, 110, 130, 72, 111, 92, 129, 164, 55, 112, 60, 171, 142, 28, 59, 113, 62 |
| NA      | 11     | 17, 156, 188, 189, 59, 147, 26, 33, 194, 197, 102 |
• communication issues and trust; and
• predictions to support software engineering processes, i.e., bug triage, defect prediction, and build failure prediction.

| Title                                                                 | Authors                                      | Year | #Cit. |
|---------------------------------------------------------------------|----------------------------------------------|------|-------|
| An empirical study of speed and communication in globally distributed software development | James D. Herbsleb, Audris Mockus             | 2003 | 1061  |
| Individual Centrality and Performance in Virtual R&D Groups: An Empirical Study | Manju K. Ahuja, Dennis F. Galletta, Kathleen M. Carley | 2003 | 608   |
| Mining email social networks                                         | Christian Bird, Alex Gourley, Premkumar Devanbu, Michael Gertz, Anand Swaminathan | 2006 | 586   |
| The social structure of free and open source software development    | Kevin Crowston, James Howison                | 2005 | 553   |
| Identification of Coordination Requirements: Implications for the Design of Collaboration and Awareness Tools | Marcelo Cataldo, Patrick A. Wagstrom, James D. Herbsleb, Kathleen M. Carley | 2006 | 444   |
| Socialization in an Open Source Software Community: A Socio-Technical Analysis | Nicolas Ducheneaut | 2005 | 426   |
| Improving Bug Triage with Bug Tossing Graphs                         | Gaeul Jeong, Sungmin Kim, Thomas Zimmermann | 2009 | 379   |
| The Open Source Software Development Phenomenon: An Analysis Based on Social Network Theory | Gregory Madey, Vincent Freeh, Renee Tynan | 2002 | 326   |
| Socio-Technical Congruence: A Framework for Assessing the Impact of Technical and Work Dependencies on Software Development Productivity | Marcelo Cataldo, James D. Herbsleb, Kathleen M. Carley | 2008 | 270   |
| Latent social structure in open source projects                      | Christian Bird, David Pattison, Raissa D'Souza, Vladimir Filkov, Premkumar Devanbu | 2008 | 262   |
Answer to RQ 4a: There are many publications on DSNs with a high citation count. The most influential publications address a very diverse number of topics, which highlights that there are many use cases for DSNs in software engineering research.

4.6. Influential Authors
We identified 356 different authors who contributed to the literature on DSNs. We use a bibliometric approach to identify the most influential of these authors, based on three different indicators: 1) the number of citations of all publications on DSNs; 2) the number of publications on DSNs; and 3) the
number of publications on DSNs we identified as influential (Section 4.5). We consider the top-5 authors in each category to be the most influential. For the bibliometric data we collected, this means that an author has to have at least 1275 citations, 8 publications, or 2 influential publications to be considered as one of the most influential authors.

Table 7 shows the 12 most influential authors we identified according to these criteria. Below, we briefly summarize the research directions of the influential authors. We discuss authors that frequently collaborated with each other as a group.

- James D. Herbsleb, Kathleen M. Carley, and Marcelo Cataldo are co-authors of two influential publications as well as several other publications. Herbsleb and Carley are both professors at Carnegie Mellon University, where they were the advisors of Marcelo Cataldo for his PhD. Their work covers structures and collaboration in global software engineering as well as socio-technical congruence within projects.

- Premkumar Devanbu was the PhD advisor of Christian Bird, who wrote his dissertation on DSNs. Their work addressed social structures and openness of open source projects, as well as build failure prediction.

- Kevin Crowston was the PhD advisor of James Howison, who wrote his dissertation on DSNs. Their work addressed community structures for open source software development.

- Daniela Damian collaborated with different authors as part of her work on communication between developers from different perspectives.

- Manji K. Ahuja collaborated with Kathleen M. Carley who was part of her PhD thesis committee. Their joint work analyzed community structures in global software engineering. Later, she worked on collaboration issues in global software engineering with respect to trust.

- Gregory Madey was the lead author of the first paper on DSNs we identified. He enabled many early papers through the SourceForge Research Data Archive [9].

- Thomas Zimmermann contributed to works that solve collaboration problems through an analysis of socio-technical aspects. The goal was to enhance developer communication, as well as describing how DSNs may be used to bug tossing as part of the triaging process.

- Vladimir Filkov, who contributed to different aspects, including homophily, developer initiation into projects, communication behavior, as well as general structural aspects of DSNs.
Table 7: Most influential authors according to the number of citations, number of publications, and number of influential publications.

| Author                  | #Cit. | #Pubs. | #Influential Pubs. |
|-------------------------|-------|--------|--------------------|
| James D. Herbsleb       | 2137  | 7      | 3                  |
| Kathleen M. Carley      | 1377  | 4      | 3                  |
| Christian Bird          | 1316  | 8      | 2                  |
| James Howison           | 1275  | 6      | 2                  |
| Kevin Crowston          | 1275  | 6      | 2                  |
| Premkumar Devanbu       | 1273  | 9      | 2                  |
| Daniela Damian          | 955   | 10     | 2                  |
| Marcelo Cataldo         | 921   | 6      | 2                  |
| Manju K. Ahuja          | 869   | 2      | 2                  |
| Gregory Madey           | 651   | 8      | 2                  |
| Thomas Zimmermann       | 584   | 2      | 2                  |
| Vladimir Filkov         | 371   | 8      | 1                  |

4.7. Important Venues

The identified papers were published in 89 different venues, i.e., journals, conferences, and workshops. Table 8 lists the venues at which most papers on DSNs were published. Three conferences stand out: the International Conference on Open Source Software (OSS), the International Conference on Software Engineering (ICSE), and the International Conference on Mining Software Repositories (MSR). 22% of all papers on DSNs were published at these three venues. This is not surprising, as most publications analyse open source projects or ecosystems and employ software repository mining techniques. The ICSE is the top conference in the software engineering field, which highlights that there are also papers of outstanding quality on DSNs. We note that the venues with most publications are mostly conferences. The only two journals that made it into this list are Empirical Software Engineering and Information and Software Technology. However, there are also publications in other premier software engineering journals: three in the IEEE Transactions on Software Engineering [100, 148, 174], two in the Journal of Systems and Software [78, 95], and one in the ACM Transactions on Software Engineering Methodology [47].

Answer to RQ 4c: The papers on DSNs were published in 89 different venues, including journals, conferences, and workshops. The most prominent venues are the ICSE, the OSS, and the MSR. Only two journals are in
Table 8: Most important publication venues determined by the number of papers published. We omitted labels like IEEE, ACM, or similar from the conference names, as they often changed slightly throughout the years.

| Venue                                                                 | #Pubs. |
|----------------------------------------------------------------------|--------|
| International Conference on Software Engineering (ICSE)             | 15     |
| International Conference on Open Source Software (OSS)              | 15     |
| International Conference on Mining Software Repositories (MSR)      | 13     |
| (Workshop until 2007, Working Conference until 2015)                |        |
| Conference on Computer Supported Cooperative Work (CSCW)            | 9      |
| International Conference on the Foundations of Software Engineering (FSE) | 6      |
| Asia-Pacific Software Engineering Conference (APSEC)                | 6      |
| International Workshop on Cooperative and Human Aspects of Software Engineering (CHASE) | 6      |
| Empirical Software Engineering, Springer                            | 5      |
| Information and Software Technology, Elsevier                       | 5      |
| International Conference on Global Software Engineering (ICGSE)     | 5      |
| International Conference on Software Maintenance and Evolution (ICSME) (ICSM until 2013) | 5      |
| Hawaii International Conference on System Sciences (HICSS)          | 5      |

4.8. Importance over Time

Another interesting aspect is the importance of DSNs over time measured by the number of publications per year. Figure depicts the number of papers published every year since the initial publication by Madey et al. in 2002. The topic quickly gained traction in the research community with rising numbers of publications until the interest became steady with 11 to 21 publications per year between 2005 and 2013. There seems to be a slight decline in the interest in DSNs since 2014 with only 9 to 10 publications per year since then.

Answer to RQ 5: There is a high interest in DSNs research since 2005, with a potentially slight decline in recent years.

5. Discussion of Open Issues

Our mapping study shows that DSNs are a versatile method for software engineering research. Mostly, they are used for the analysis of social structures and communication. However, the applications of DSNs range beyond that, e.g., for predictive purposes. Within this section, we discuss open problems in DSN research.
5.1. General Issues

Here, we discuss general issues within the current body of work on DSNs, that should be addressed by future work.

5.1.1. Lack of Guidelines

There are no guidelines on how to conduct DSN research. Therefore, the studies on DSNs are performed and described very heterogeneously. This is not an issue in itself, as heterogeneity can also be positive if different aspects are analyzed. Moreover, many publications perform well-designed case studies and report all important data regardless of the lack of guidelines. However, we observed several issues that result from the inconsistent way studies with DSNs are performed:

- lack of reporting of the exact data sources and/or selection criteria for case study subjects;
- lack of reporting of important meta data about the study, e.g., number of projects, number of people; and
- lack of reporting of pre-processing steps performed with the data, e.g., to merge identities in case the same people used multiple aliases.

The development of guidelines for research on DSNs can, therefore, help to enhance the quality of DSN research in general.

5.1.2. Studies with High External Validity

Our data shows that many results regarding DSNs were obtained only on very few projects, i.e., over 71% of the publications used less than 11 projects to conduct their research. While this does not mean that the results are wrong or would not generalize to other contexts, this poses a threat to the generalizability of results. This problem is to some degree further aggravated, because there is an overlap in the data that is used, i.e., multiple studies using the same data, sometimes the same single project (e.g., IBM Jazz or the Global Studio Project).
Moreover, we noted a strong relation between the data sources and the size of studies. Figure 5 shows the size of the studies with relation to the data source. The larger circles mean more publications. Almost all publications with large numbers of people and projects were based on data from forges. Thus, an open issue considered for all future publications is to use larger sample sizes regarding the number of projects, to enable a better generalizability of results. This could either be done by harnessing data from forges or by collecting data for more projects from other data sources.

5.1.3. Lack of Replications

There is general lack of replications in DSN research. The publications are more or less independent of each other, the exception being multiple publications by the same authors building on each other. We did not find any study that explicitly tried to replicate prior results. The lack of replications is especially problematic due to the often very small numbers of projects considered (see above). Thus, we believe that replication studies on DSN research are required for all research directions so far.

5.2. Open Topics

Here, we discuss potential future directions of DSN research.

5.2.1. Inter-company Collaborations

Since more and more companies contribute to open source software and/or develop their own software products as open source, the collaboration between developers of competing companies becomes an important issue. If developers from competing organizations contribute to the same project, this could lead to issues within a project, that could be analyzed through DSNs, e.g., with respect to team formation, onboarding, collaboration problems, and even impacts on
the socio-technical congruence of projects. Within our mapping study, we only discovered one publication in this direction [161].

5.2.2. DSNs from Multiple Sources

The use of multiple sources for DSN studies allows a deeper analysis of developer communities. For example, how does the community on a ML differ from the community that can be observed in pull request discussions or in an ITS? Can we infer something about onboarding of developers from their integration in different DSNs? Do projects that use an ITS and a ML exhibit different collaboration properties than projects that just use an ITS or a ML? What exactly is the temporal-spatial relationship between the DSN structures of different sources? Does research regarding the team formation of projects based on MLs yield the same results as research on team formation on ITSs? How does migration to a new ITS affect the community structure? All of these are currently open questions. Especially the comparison of DSNs that are based on different data sources has been neglected so far, with only a single publication that directly compares the DSN structure obtained from ITS data with that obtained from VCS data [199].

5.2.3. Applications using DSNs

The current literature on DSNs has a strong focus on understanding community structures and the implications of the community structure on issues like developer roles, team formation, and collaboration behavior. However, there are only relatively few actionable applications of DSNs. CodeBook [156] is a notable exception that demonstrates how DSNs can be used to improve the daily life of software developers. While other publications also study applications of DSNs, e.g., for defect prediction, failure prediction, or developer recommendations, they are mostly not accompanied by a tool that makes the research actionable for practitioners. The tool papers that we identified cover mostly the visualization of DSNs. While visualizations are a useful tool for the analysis of communities, they are not actionable applications of DSNs. We believe that research that produces actionable tools can have a big impact, e.g., on already considered issues like bug triage or developer recommendations.

5.2.4. Data sets

We only identified a single publication that published a DSN as data set. While there are other publications that are based on public data sets, e.g., the source forge dump [9], these data sets are not yet DSNs. They only contain the data necessary to create a DSN. While there are certainly use cases, in which new DSNs must be created, e.g., because different information is used to create links between developers, there are also cases for which dedicated data sets on DSNs would have advantages. For example, benchmark data sets could allow, e.g., to compare different approaches for developer recommendation or the identification of core developers. Moreover, the collection of data from a large amount of software repositories can be very time consuming. Data sets
for a large amount of projects could help with this issue, and, e.g., enable larger
studies with MLs as sources for projects.

6. Related Work

Our systematic mapping study is not the first literature study that covers
DSNs. Within this section, we discuss related literature studies on DSNs, their
differences to our work, and how we utilized them as sanity checks for our work.

Closest to our work is the survey by Zhang et al. [3]. Similar to our work, the
authors analyzed the data sources, as well as topics that were addressed with
DSNs. However, there are several notable differences between the work by Zhang
et al. and our work. First, the search strategy by Zhang et al. is different from
ours. They used the search term "developer network" and identified 20 publi-
cations related to DSNs within the first 50 hits on Google Scholar. Using these
publications as seed, the authors performed one round of forward/backward
snowballing and identified a total of 86 primary studies this way. In compari-
son, we use more search terms and multiple search engines, consider 750 instead
of 50 hits per search term/search engine, and performed exhaustive backward
and forward snowballing until no further papers were identified. Moreover, the
focus of the presentation from Zhang et al. differs from ours. We provide a
systematic mapping of approaches to topics through inductive coding. In compari-
son, Zhang et al. provide a more detailed description of different approaches
to address research topics, but no systematic mapping. We used the research
topics they describe as starting point for our inductive coding. Another differ-
ence to our work is that Zhang et al. also report on the metrics that were used
for the analysis of the DSN, an aspect that is not covered by our mapping study.

The literature study by Tamburri et al. [4] uses grounded theory to identify
different types of social structures within open source software development.
Thus, their focus is different from ours, which is on DSNs in general, not on social
structures. However, DSNs play an important role in the study by Tamburri et
al. and are part of the literature that they identify. Due to the different focus,
the search strategies also differ. Most importantly, the search by Tamburri et
al. also covers search terms like "organizational", "knowledge community" and
similar to account for the different focus. Moreover, the search engines used
are different from ours. They used SCOPUS, Web of Science, EBSCO, JSTOR
knowledge storage, Wiley InterScience and ProQuest in addition to the search
engines we used. On the other hand, we used Google Scholar, which was not
used by Tamburri et al.. The authors identified 143 publications for their study.

Manteli et al. [5] performed a literature study to analyze DSNs with respect
to global software development. Their focus was on coordination, cooperation,
and communication aspects of global software development. This scope of this
survey is narrower than our mapping study of DSNs without further restrictions.
This shows in the difference in search terms and inclusion criteria. Moreover,
there is a difference in search engines used. Manteli et al. used EBSCO and
Wiley InterScience in addition to the engines we used, but did not use Google
Scholar. The authors identified 23 primary studies on DSNs with a relation to global software development.

Abufouda and Abuwaik [6] performed a systematic literature review on DSNs with the goal to identify how reliable constructed social networks are. This goal is different from our general focus, which shows, e.g., in the different exclusion criteria. The authors used the same search engines we also used, with the exception of Google Scholar which was not considered. The authors identify 23 primary studies that meet the criteria for their survey. The data the authors collected is very detailed with respect to the required description of the model and covers aspects like vertex types, edge types, and validation criteria. Thus, the work by Abufouda and Abuwaik focuses on evaluating aspects related to the internal validity of studies. In comparison, we collect data related to the external validity of DSN studies in our work, i.e., the scope of the analysis that is conducted.

In addition to our comparison with related work above, there are several differences between our work and all the related literature. No other work performed a bibliometric assessment of influential authors, papers, and venues. Moreover, no work in the literature provides information about the scope of the networks, i.e., the number of projects and participants that are analyzed through DSNs in a publication.

7. Conclusion

This article presents the results of our systematic mapping study on DSNs. We identified 194 primary studies published between until 2017. Our results show that DSNs were used for the analysis of many different software engineering research topics since their initial use in the year 2002 [41]. Our mapping study provides insights into research directions, data sources, the size of studies, as well as a bibliometric assessment of the field. Based on our results, we determined open issues in the state of the art. Through this, we provide a valuable resource for researchers to guide future research on DSNs.
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Primary Studies

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