Sustainability in Software Engineering

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***Abstract*—The intersection between software engineering research and the problems related to sustainability and green IT has been the subject of increasing attention. In spite of that, we observe that sustainability is still not clearly defined, or understood, in the field of software engineering. This lack of clarity leads to confusion about e.g. what is relevant to measure or the research implications over time or space.**

This paper provides an overview of how the research so far has defined sustainability, and how this definition has been used to guide which research areas. To this end, we carried out a systematic mapping study for selecting, classifying and analyzing relevant publications. In this study, we investigate which knowledge areas and which time scope of sustainability effects are mostly targeted in scientific research. Our analysis shows research trends and discusses gaps to be filled.

Keywords*—*Sustainability, Software Engineering, Systematic Mapping Study.

I. MOTIVATION

In the past years, climate change and an increasing awareness for social inequality have made sustainability a growing concern in a wide variety of disciplines. The discipline of Software Engineering (SE) is no exception. A widely quoted definition characterizes sustainability as the ability to meet "the needs of the present without compromising the ability of future generations to meet their own needs"[5]. However, when applied to SE, it is unclear what specific aspects of Software Engineering and the resulting software systems it refers to. As of now, there is no agreed-upon definition for sustainability in the context of Software Engineering, and existing research approaches rely upon different notions, ranging from e.g. sustainability of the SE process [7] itself to specific software applications designed to support sustainability goals impacting other disciplines [8].

Sadly, sustainability is regularly used in research papers as a vague buzzword, where the authors' notion of the term is not stated clearly and has to be extrapolated from the text. For a better understanding of existing papers and to give researchers a motivation to provide a clearer definition of their approach w.r.t. sustainability, a clear classification of all aspects of sustainability would be desirable. However, before any attempt to establish such a framework for sustainability research, it is necessary to establish an overview of current research, in order to achieve a better understanding of which factors in software engineering are relevant for sustainability and how effects propagate throughout the software engineering lifecycle.

To this end, this work provides an overview of the current state of the art by addressing the following main research question (RQ):

How is sustainability currently defined in the context of Software Engineering?

To answer RQ, we analyzed a wide range of primary studies and employed the *systematic mapping study* research method as defined by Peterson et al. [17]. This type of secondary study gives an objective framework for structuring and analyzing the research domain and is a suitable means for identifying trends in research.

II. METHODOLOGY

In order to ensure a traceable and reproducible process, the following section will define the protocol used in our systematic mapping study.

A. Research Questions

For the sake of a more structured approach for information extraction, our main RQ has been refined into the following detailed research questions:

RQ1: Which sub-disciplines of SE, if any, does the definition relate to? SE is a wide field encompassing, according to the Software Engineering Body Of Knowledge (SWEBOK, [4]), 15 sub-disciplines. Mapping existing research efforts onto these sub-disciplines will provide an overview of which areas have witnessed growing research efforts on sustainability, and where potential for additional research lies.

RQ2: Which time scope is considered in the definition? Sustainability is a concern for the future. However, the perceptions differ as to how far the future influence of an activity in sustainable development extends. Sustainability measures have not only direct primary effects, but also indirect secondary or tertiary effects in the long term. Therefore, we are interested to establish how far SE researchers have considered these effects in their notion of sustainability.

RQ3: How did the definition develop over time? Especially during the last years, the topic of sustainability has seen a strong increase in research activity in software engineering. We are interested in how this may have influenced the way sustainability is understood and if there has been any shift in focus of research over time.

B. Search Strategy

The primary studies identified in this mapping study were retrieved by combining the following two search strategies.

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The first strategy used an **automatic extraction** approach (see left-hand side in Fig. 1) [10] supported by the Smart Topic Miner (STM) [12], which is the tool used by Springer Nature for classifying conference proceedings in the field of Computer Science[1]. STM builds on the Rexplore system[2] and characterizes publications according to the research topics from the Computer Science Ontology (CSO), a large-scale OWL ontology of research areas. It does so by associating to a scientific paper all the concepts in CSO whose label is found in the title, the abstract, or the keyword set, and all super-areas and synonymous of those. For example, a publication associated with the term "xADL" would also be tagged with higher-level topics such as "Software Architecture Description Languages", "Software Architecture", "Software Engineering", and "Computer Science". CSO currently includes 17K concepts and was generated by running the Klink-2 ontology learning algorithm [11] on the Rexplore dataset, which consists of about 16 million publications, mainly in the field of Computer Science. For the purpose of this analysis, we used only the branch describing the Software Engineering domain[3], which was reviewed by five domain experts. We extracted the primary studies by querying a Scopus[4] dump from the 1980-2013 period, and selecting all publications which 1) were tagged by the STM with the CSO concept "Software Architecture", and 2) contain in the title, in the abstract, or in the keyword set at least one of the following keywords:

> *Ecologic Ecological Ecology Sustainable Sustainability Biodiversity Ecosystem Ecosystems sustainable development environmental impact climate change environmental protection green*

This automatic extraction strategy has the obvious advantage of being able to process a very large dataset of publications with no human intervention. However, it presents some limitations. First, the underlying Scopus dataset does not include papers published after 2013, therefore we could not apply this technique on the most recent publications. Secondly, the terms in the papers can sometimes be misleading, and thus a further human intervention is necessary to filter out not relevant publications.

The second search strategy used the primary studies from a **previous literature study** (see other input at left-hand side of Fig. 1), a systematic literature review (SLR) on sustainability in SE. Manually performed on the ACM Digital Library, IEEE Xplore and SpringerLink, this SLR did include all publications that were indexed in the used libraries at the time of the extraction in 12/2016 and hence complemented the results of the automatic extraction strategy.

In particular, it used the following search string, implemented in each database's specific format:

> *allInTitle: (sustainab* OR green* OR ecolog*) AND software*

[1]Demo available at rexplore.kmi.open.ac.uk/STM2_demo/
[2]http://technologies.kmi.open.ac.uk/rexplore/
[3]Available at http://rexplore.kmi.open.ac.uk/data/SE-ontology.owl
[4]https://www.elsevier.com/solutions/scopus

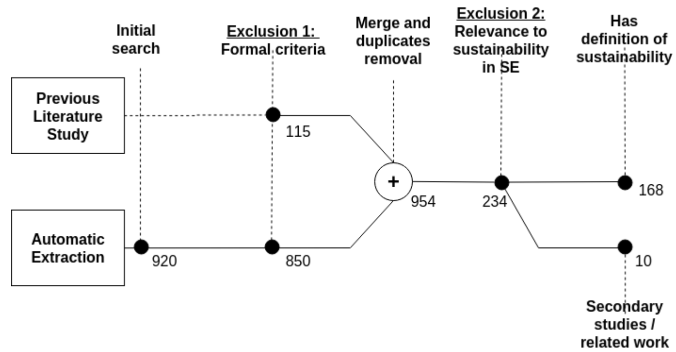

Fig. 1. Overview and numbers of the search and selection process

C. Study Selection

From the publications returned by the two search strategies, after a removal of duplicates, a number of inclusion and exclusion criteria was applied to the dataset to eliminate those titles that were formally not acceptable or not relevant. Figure 1 shows an overview of the different steps performed on the data sets.

1. Elimination according to formal criteria: In order to be admissible for evaluation, publications had to fulfill the following inclusion criteria:

- I1 - Published in English
- I2 - Peer-reviewed
- I3 - Available as full-text.

Set 1 of publications from the manual SLR had already been filtered according to these formal criteria and contained a total of 115 publications. Set 2 consisted of 920 papers that were automatically extracted by the automatic extraction approach, of these 850 publications remained after elimination according to these criteria.

2. Merging and duplicate removal: Merging the two data sets and removing the duplicates between both sets left 954 papers to be processed further.

3: Elimination according to relevance: The publications were then analyzed for their relevance to the topic of sustainability in Software Engineering. For this purpose, the following inclusion and exclusion criteria were defined:

- E1 - *No reference to sustainability or Green IT:* Some of the chosen keywords, although often connected to the aspect of sustainability, are also used in other contexts in SE. For example, “environment" may be used in the context of environmental sustainability, but frequently refers to the “software execution environment". This resulted in a large number of false positives that were not relevant to sustainability or green IT.
- E2 - *Sustainability in the context of software use:* Studies referring to software as a tool that is used to achieve sustainability in other disciplines, such as agriculture, education, or supply chain management, were explicitly excluded.
- I4 - *Sustainability in the context of software engineering:* The focus of our study lies in the creation process of software and its sustainability

properties and the way it influences sustainability properties of the software product.

4. Related work: Ten extracted publications pursued a research goal similar to ours, i.e. to analyze sustainability research in software engineering. Accordingly, we decided to treat them separately and discuss them in the related work section.

5. Extraction of sustainability definitions: Finally, all publications were analyzed to elicit the notion of sustainability as meant by the authors. All papers containing a clearly stated definition of sustainability, either directly or as a quote, were included. Publications where a definition and focus could be derived implicitly from context, application or examples were also included. All cases that did not allow to derive a clear definition or merely seemed to be using “sustainability" as a buzzword were discarded, which resulted in a final count of 168 primary studies. The extracted definitions were analyzed for a number of characteristics that allowed us to map the differences between the various research works in an accurate way. The overall research focus of each primary study was mapped to a Knowledge Area, as defined in the SWEBOK [4]. Apart from that, the author’ sustainability approach was characterized according to its focus on either the process or the product, as well as the considered time scope for sustainability within the software engineering lifecycle. We also extracted the order of effects taken into account by the authors as either immediate, enabling or systemic and noted down which of the environmental, economic, social and technical dimensions of sustainability were considered. Section III-B goes into detail as to how exactly this classification was performed.

Due to space limitations, a complete list of all papers in the final selection including their extracted classification is made available online[5].

III. Results

The following section will first present an overview of the related work we identified among the extracted papers. We will then first go into more detail on the classification we used to analyze the single publications’ definition on sustainability and then make use of the data gathered with this classification in order to address the research questions we defined in section II-A.

A. Related Works

This study is by far not the first endeavour to improve the understanding of sustainability in Software Engineering. As mentioned previously, the literature search also resulted in a total of 10 secondary studies that had similar research goals with respect to sustainability in SE, i.e. providing a basis for further research by compiling definitions, defining common research goals or giving an overview of the development of the research area. This section gives an overview of these publications.

Three of them are systematic literature studies aiming to give an overview of the state of research on sustainability in SE or on SE for Sustainability. Two publications aim to provide reference models for the sustainable development of software by giving an overview of sustainability aspects, providing a sustainable software engineering lifecycle model, or defining metrics. Two general research papers reflect on current definitions of Green IT and sustainability, whereas one manifesto created by a large number of sustainability researchers from software engineering aims to further the discussion and awareness of sustainability in SE research. One case study reflects on changes and variations in the development of sustainability over time by taking a public ICT project in India as an example. And, finally, one paper establishes a plan for integrating sustainability education into the curriculum of Software Engineering students.

[5]https://tinyurl.com/y94x8ygp

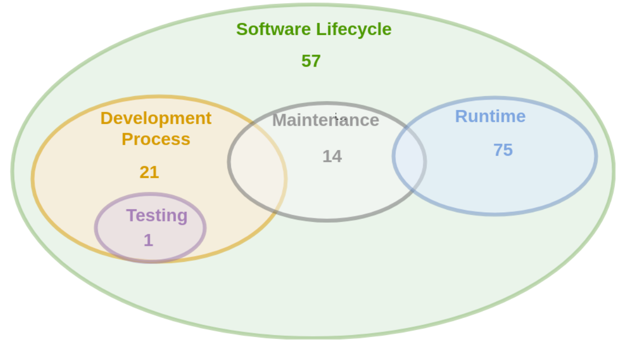

Fig. 2. Distribution of publications over the time scopes of sustainability

B. Classification

The 168 primary studies including a clear definition of sustainability were categorized according to a number of criteria, in order to give an overview about prevailing notions of sustainability and Green IT in SE research. Before answering the research questions we will now describe the strategy and rationale for this classification.

1) SWEBOK Knowledge Areas: Since one of the goals is to identify areas of increased activity of sustainability research, we assigned all publications to knowledge areas as they are defined by the SWEBOK[4]. These were chosen according to the research area focus of the paper and, as not all publications clearly belonged to a single knowledge area, up to 2 knowledge areas per paper were assigned.

2) Focus on Process or Product: SE research on sustainability has two focus areas: On one hand, it focuses on making the engineering process more sustainable, for example by applying agile tactics or by sustaining an open source development community. On the other hand, there is effort to render the output, i.e. the product and its direct and indirect effects, more sustainable though measures such as energy-efficiency optimization.

3) Time scope: We are especially interested to know, which timeline researchers are taking into consideration when targeting sustainability in their research. We therefore categorize publications according to the time scope that is considered for sustainability in research, specifically the phase within the software engineering lifecycle during which the intended

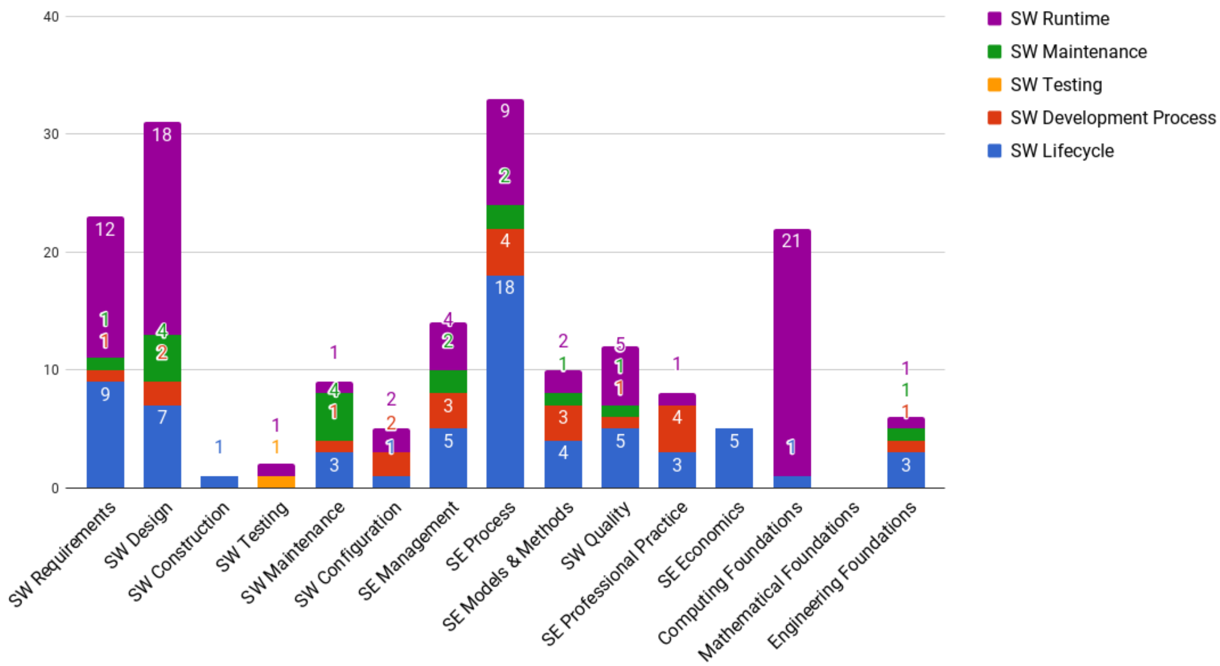

Fig. 3. Distribution of the time scope of sustainability according to each Knowledge Area

effects on sustainability manifest. Depending on their focus, we assigned the following time scope categories:

- *Development process:* papers that attempt to make the development part from the first designs to the release of a software product more sustainable by guaranteeing development speed and quality.
- *Testing process:* papers that exclusively deal with the sustainability of the testing phase as a subprocess of the development phase.
- *Maintenance process:* papers that aim to make the maintenance of a finished product more sustainable by, for example, reducing the personal, monetary and environmental cost.
- *Runtime:* papers that aim to achieve a positive effect of software on sustainability during the time of its execution.
- *Lifecycle:* papers that do not specifically focus on any of the aforementioned categories, but look at sustainability effects during the whole software lifecycle.

As an example, energy-efficiency optimization would manifest during software runtime, while optimization in the software architecture would make the maintenance phase of software more sustainable. Of course these different time scopes overlap as well: development and testing happen during the maintenance process too, albeit in a limited extent. Papers were assigned to a single category, in which the major focus lay.

4) Sustainability Dimensions: Sustainability is commonly divided into different dimensions, depending on the type of effects a product or process has. Normally considered are the environmental, economic and social dimensions of sustainability. Apart from this, we also add technical sustainability as a fourth dimension to this list, considering that a number of papers are only focusing on sustaining software on a technical level without explicitly taking other dimensions into account.

5) Effects: Software Engineering not only directly impacts sustainability in its various dimensions, but also indirectly. In order to determine to what extent authors take into account these indirect effects, all publications were also categorized into immediate (direct), enabling (indirect) and systemic impact, according to the order of effects targeted by the authors.

C. Time Scope of Sustainability

A major interest in this mapping study was the timeline that authors of papers on sustainability in software engineering took into consideration during their research. Figure 2 shows how the papers are distributed over the different categories, with Runtime being the most prominent, mostly due to a large number of papers focusing on software energy efficiency. Apart from this, research considering sustainability during the complete software lifecycle was most common.

D. Sustainability by Knowledge Area

When looking at how the selected papers are distributed over the SWEBOK knowledge areas, as presented in figure 3, a number of hotspots become immediately obvious. Software Requirements, Software Design and the Software Engineering Process feature the biggest number of papers. Computing Foundations, which covers SE areas such as networks and algorithms, is another prominent knowledge area.

Upon further inspection of how papers in these Knowledge Areas are distributed in terms of time scope, SE Process shows a stronger focus on the Software Lifecycle compared to other areas, whereas Computing Foundations has a strong focus on sustainability during Software Runtime.

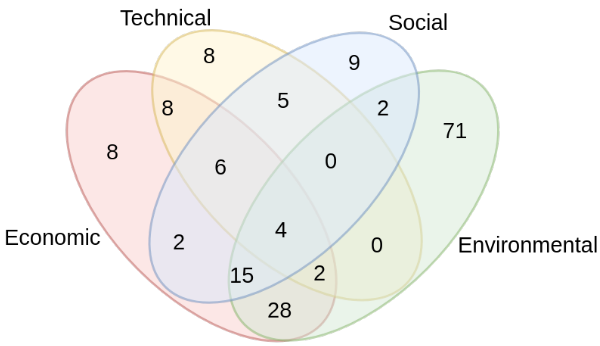

Fig. 4. Distribution of papers over the different sustainability dimensions

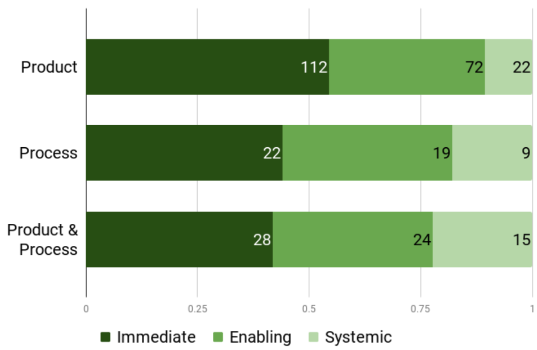

Fig. 5. Mapping of papers according to their focus and the order of effects the authors are targeting

E. Sustainability Dimensions

In figure 4, we are presenting an overview of how the definitions in all included publications are distributed over the various dimensions of sustainability. The vast majority of publications are considering environmental sustainability if not as a main concern, then at least as a partial concern. In contrast to this, technical or social sustainability are only part of the considerations in a minority of papers.

F. Sustainability Focus and Effect

In figure 5, the focus of a publication on sustainability of product, process, or both is displayed in context with the order of effects targeted by the author. Generally, the bulk of papers is solely focusing on sustainability of the product and the immediate effects it has on sustainability. In relation to that, publications that also consider the SE process, have a tendency to focus as well on secondary and tertiary effects.

G. Sustainability research over the years

Figure 6 illustrates how the number of publications on sustainability in SE has strongly increased over the years. The numbers for the years 2014-2016 are only considered preliminary, due to the limitations in the used data set mentioned in II-B. However, a trend can be seen and it becomes obvious how interest in sustainability has increased.

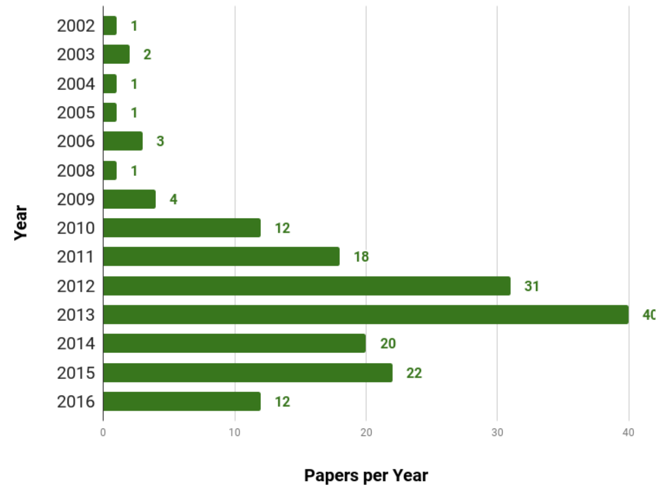

Fig. 6. Number of publications by year. Note that there are less publications for the years after 2014 due to limitations in the search strategy as detailed in section II-B

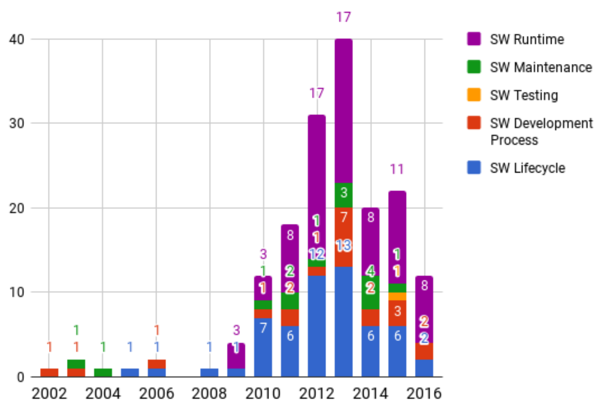

Fig. 7. Time Focus of SE research on sustainability plotted over time

One goal of this study is to examine to what extent the definition of sustainability in research has changed over time. Figure 7 shows how publications over the years relate to the time scope within the SE lifecycle that they are addressing. Of course given the low number of papers before 2008 is hard to give a comprehensive interpretation of the development of the time scope between 2008 and 2016. Still, papers treating sustainability effects during software runtime have only become prominent after 2009, while other scopes had already been addressed already earlier.

IV. Discussion

In the following, the previously presented results of this mapping study will be discussed and used to answer the our research questions. We will then discuss the extent to which the results are subject to threats to validity.

A. Research Questions

RQ1: Which sub-disciplines of SE, if any, does the definition relate to? By analyzing the distribution of publications over the SWEBOK knowledge areas (see Figure 3) we observe a clear trend: the four top-most researched areas are also those that have the most pervasive/broadest influence on the software lifecycle. These are (1) the SE Process (which includes the largest cluster of studies in sustainability research encompassing the complete lifecycle, and hence providing both a framework and a basis for research on sustainability); the areas of (2) Software Requirements and (3) Software Design (which are both activities early in the SE lifecycle and therefore have a high impact on the resulting product); and (c) the area of Computing Foundations (which provides a basis for further research on Green IT and sustainable data centers).

The remaining areas witness a significantly lower number of studies. Among them, we think that potential for further research surely exists in the area of Software Quality, especially since at least some partial aspects of sustainability, such as resource efficiency, are already established as an aspect of software quality. Similarly, Software Testing, SE Management, Models & Methods and Professional Practice are areas where already a certain amount of research exists, but in practice practitioners in these areas are largely unaware of sustainability.

RQ2: Which time scope is considered in the definition? The majority of papers either focus on sustainability during the complete Software Lifecycle or at Software Runtime only. In comparison to this, other time periods during the Software Lifecycle are less represented in research, this might be caused by the fact that sustainability during the development or maintenance process is often not explicitly defined: it comes under the name of other software quality aspects such as maintainability, efficiency or adaptability, which describe properties that influence a system's sustainability during certain lifecycle phases.

RQ3: How did the definition develop over time? Sustainability as a concern in SE is, all in all, a fairly recent topic. The majority of analyzed papers date from after 2010, after which the topic has seen a strong increase in attention. An examination of the distribution of time scopes for sustainability of these papers shows that sustainability during Software Runtime has become a major focus of research. Time-wise, this coincides with the popularization of cloud technology, and ever-growing data-centers world-wide have created a need for more resource-efficient solutions, a development that has led to awareness for Green IT and energy-efficient data-centers. Other than this increase in research activity, there is no clear change in focus over time visible in the data collected from the papers considered for this research. The papers might have to be analyzed in more detail than the approach of a systematic mapping study allows to get a clearer picture. Apart from this. all related work with a similar goal is still fairly recent, so it remains to be seen how these efforts to bring structure and attention to sustainability research in Software Engineering impacts the field. Section V will present more details on these works.

B. Threats to Validity

We identified the following possible threats to validity:

Bias of keywords: The keywords of the search as described in section II-B could have created a bias towards environmental sustainability. Mitigation of this bias, however, is difficult: Green IT is a discipline that is clearly defined as addressing environmental sustainability concerns. Analogous keywords for the other dimensions of sustainability (like social or technical) are harder to define or would be too vague, hence failing to filter publications in a reasonable manner.

Limitation of automatic extraction: The data dump on which the extraction was performed was restricted to publications until 2013 included, which becomes evident in figure 6. This weakness has been balanced by including the primary studies of a previous SLR as another source of publications after 2013.

Classification of papers: The classification described in section III-B was executed by the first author alone. As such, it may contain a personal bias. To mitigate this risk, the other authors have been consulted in case of doubt and in randomized checks.

V. Related work

Since this literature study also resulted in a number of related research publications, these will now briefly be reviewed here to complement the results of this paper.

This is by far not the first literature study with a focus on sustainability in software engineering. Penzenstadler et al. [14] performed a systematic literature review on the state of sustainability research in SE and divide the focus of research in a similar manner as has been done in this paper for the targeted time scope of research. The defined aspects attribute sustainability research to the development process, the maintenance process, system production or system usage. A systematic mapping study performed later by the same authors [16] maps publications to knowledge areas, but identifies different areas than in this paper as hotspots, with Models & Methods and Software Design being more prominent. This might be due to the fact that Green IT was not included as a topic specifically. Notable venues, authors and guidelines have been identified in a mapping study by Berntsen et al.[3].

A research paper by Penzenstadler [13] takes up the concept of aspects for defining and delineating sustainability in SE as presented in the previously described SLR, and elaborated on these aspects. A comprehensive description of the state of the art with an overview about established descriptions, definitions and models, with a focus on the Green IT aspect of sustainability, is given by Calero and Piattini [6].

The frequently referenced GREENSOFT model publishes by Naumann et al. [9] aims to provide a structure and strategies in order to facilitate Green IT and provide a basis for sustainable software projects. The Generic Sustainable Software Model presented by Amri et al. [1] characterizes software sustainability according to the 5 dimensions environmental, technical, social, individual and economic. Sustainability values are assigned to a SE project according to these dimensions.

Unusual among the list of related work is the so-called *Karlskrona Manifesto for Sustainability Design* [2], signed by a large number of researchers in the field, which aims to further the dialogue about and foster awareness for sustainability design in Software Engineering. The accompanying paper delineates current definitions of sustainability and related aspects and concepts.

Finally, in order to foster awareness for sustainability already in young academics, Penzenstadler and Fleischmann [15] propose a plan for integrating sustainability concepts into the curriculum of Master students in Software Engineering.

VI. Conclusion

The systematic mapping study presented in this paper had the goal to give an overview as to how researchers in the domain of Software Engineering defined and approached the omnipresent issue of sustainability. Taken on one hand from a previously executed literature study and on the other hand extracted automatically, we analyzed a total of 1035 papers on sustainability and Green IT. Given a suitable data set of publications as a basis, this automatic extraction algorithm significantly decreases the manual effort necessary for the execution of a study, however, it does not entirely eliminate the manual review process.

The analysis of the finally selected papers emphasizes how relatively new sustainability is as an issue in software engineering. Research is strongly focused on the environmental aspect and the direct effects of the software engineering process and the resulting product. Systemic effects of software and the SE process are still getting relatively few attention. Efforts in related work to formalize sustainability as part of the SE process have been made only during recent years and have yet to make their way into official standards and models.

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