Systematic Literature Study on Sustainable Software

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1. Introduction

One of the biggest challenges of this generation is conserving the environment and minimizing the further damage we do to our planet. With Information Technology becoming a key part of our everyday lives, the sustainability of the software we use has become increasingly important. This has led to an emergence of research on sustainability in software engineering in the last decades.

In 2014, Penzenstadler et al., performed a systematic mapping study on Software Engineering for Sustainability (SE4S) [1]. This study was published almost three years ago, and a lot of research on Software Sustainability has been done since. The aim of this paper is to provide an overview of the current research done on this topic.

One common definition of sustainability is "meeting the needs of the present without compromising the ability of future generations to satisfy their own needs". In this research we consider not only sustainability in the environmental sense, but also technical sustainability, economic sustainability and social sustainability.

In this paper, we differentiate between two interpretations of Software Sustainability, namely software to achieve sustainability and sustainability of software itself. Software to achieve sustainability could for example be simulation software that helps with the construction of energy neutral houses. In this paper we will refer to this interpretation as software FOR sustainability. An example of sustainability OF software itself could be making software more energy efficient.

The study design, including the research question and search strategy, are described in Section 2. We follow by presenting the results in Section 3 and discussing them in Section 4. Then we will briefly consider the threats to validity in Section 5 and finally discuss the conclusion in Section 6.

2. Study design

In this section we describe the study design in terms of research questions, search and selection strategy and data extraction.

2.1 Research questions

The goal of this Systematic Literature Review (SLR) [2] is to give an overview of the research published on sustainability of software engineering and software used to achieve sustainability. This leads to the following three research questions:

RQ1 How does the research done on sustainability of software compare to the research on software to achieve sustainability?

As discussed in the introduction, we distinguish two interpretations of Software Sustainability, namely software to achieve sustainability (FOR) and sustainability of software (OF). We want to compare the research done on these two interpretations. Answering this question will allow us to see where the focus lies of researchers regarding Software Sustainability.

RQ2 What research topics are being addressed?

With this question we hope to gain a better understanding of the addressed research topics that will help us classify the research done on software sustainability. We will present an overview of the most common research topics, as well as identify the most and least commonly addressed research topics. Answering this question will allow us to propose further guidance in the future research to be done on software sustainability. Selected primary studies are assigned a research topic based on the SWEBOK v3 Guide to the Software Engineering Body of Knowledge [3], which contains a total of 15 different research areas.

RQ3 How has the research evolved over time?

In our study we are curious to discover the evolution of the research topics addressed in previous question over time. Answering this question will allow us to make conclusions on the evolution of research trends, therefore identifying the current state of research done on software sustainability. Furthermore, we hope to identify the research topics that are currently trending. We will do this by relating the previously defined research topic to the year of study publication.

RQ4 Which application domains have been considered?

Apart from the research topics addressed in our selected primary studies, we are also interested in discovering the practical application of the research done on software sustainability. Identifying the application domain of the selected primary studies will allow us to make conclusions on the well-researched domains and provide suggestions for future research.

2.2 Search strategy

This section defines the search strategy used to gather the studies to be considered for this research and the sources from where we obtained our primary studies.

Information Sources

In this study the search was performed on a total of three different digital libraries: ACM, IEEE Xplore, Springer. Initially, the search included two additional digital libraries, namely DBLP (Computer Science Bibliography) and Web of Science. However, the DBLP library was excluded from the results because it did not allow for a query on article titles. Furthermore, we found that searching Web of Science was inconsistent: on different machines we got different results for the same query. After initial inspection of the results we concluded that the Web of Science results were mostly already indexed by other digital libraries (for example IEEE) and the remainder contained numerous articles that were not adequate for our study. Therefore we have decided to exclude the search results of Web of Science articles completely.

Search String

The search string used in this study is an alteration of a search string used in the previous systematic mapping study produced by Penzenstadler et al [1]. Main goal of the search string used is to capture all results related to sustainable software and sustainability achieved by using software. Therefore, the first part of the search string ties the results to sustainability related topics, while the second part of the search string is an addition that ties the sustainability topics to software related fields. The search string used on all libraries is:

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

Compared to the search string of Penzenstadler et al., we have excluded the terms related to *requirements engineering* because in our research we are interested in a broader scope, including all articles on software sustainability and not only on requirements engineering.

Given below is a table presenting the final search string implementations on each of the digital libraries.

Search Execution

We use the search string to execute the search on all the databases specified above. Furthermore, the search was executed on **article titles** only, to narrow the results while maintaining their relevance to this study. All results were stored and consolidated using Zotero and duplicates were removed.

Table 1: Final search string implementations

Library	Exact search string
ACM	acmdlTitle:(sustainability green ecology) AND acmdlTitle:(software)
IEEEXplore	(("Document Title":sustainab* OR "Document Title":green* OR "Document Title":ecolog*) AND "Document Title":software)
Springer	title contains: software&(sustainab*|green*|ecolog*)

2.3 Study selection

Study selection criteria

The in- and exclusion criteria are outlined in Table 2. An article is either included or excluded from the literature review based on these criteria.

Study selection procedures

After collecting all papers from the databases and removing duplicates, we found that a lot of the titles from the results did not match the search string. This led to the first exclusion round, where we applied a filter to exclude all papers for which the title did not match the search string. It should be noted that, if databases return articles that do not match the search string, we can not be sure that they leave out articles that do match the string.

In the second exclusion round, all titles were read and if it was clear that the paper did not fit the inclusion criteria, the paper was excluded. In this round we were quite conservative; we excluded only the papers for which it was evident that they should not be included and if both researchers agreed on the exclusion. After this round 245 papers remained. For feasibility reasons, we performed the analysis only on a subset of 200 papers (100 for each researcher). The 45 papers were randomly excluded.

In the last round, we read the full text for all remaining papers to decide on in- or exclusion. For the papers for which one of the researchers was unsure on the decision, the researchers discussed the paper to come to a mutual conclusion.

In the last round, we read the full text for all remaining papers to decide on in- or exclusion. The remaining papers were split equally between the two researchers. If a researcher was unsure of the decision on the inclusion or exclusion of a paper, the paper was reviewed by both researchers and each of them proposed its decision, after which a mutual conclusion was made on the in- or exclusion of the related paper.

Table 2: Inclusion and exclusion criteria

Inclusion	Exclusion
I1 *The title of the paper matches the search string* Rationale: In order to limit the search results to feasible numbers, we have decided to focus only on the papers whose title matches the search string.	**E1** *The title of the paper does not match the search string* Rationale: In this study we will not focus on papers that match the search string in abstract or full-text. Our pretests showed that the results would be unfeasible to manage unless we imposed title-related search limits.
I2 *The study is focused on sustainability in relation to software* Rationale: the study must relate sustainability to software in one of the following two ways: sustainability of the software itself (for example, its code) or using software to achieve sustainability (in a system).	**E2** *The study is not focused on sustainability in relation to software* Rationale: in this study we will not focus on papers that do mention sustainability but not in a context related to software.
I3 *The study is peer reviewed* Rationale: the goal of our systematic mapping study is to collect information obtained only from peer reviewed studies as those are proven to be more sound.	**E3** *The study is grey literature, a thesis or book* Rationale: this study will not take into account any grey literature, i.e. technical reports, industrial reports and white papers. Books are also excluded since it is not feasible to read the full book in the scope of this study. Finally theses, be it master or phd theses, are excluded, since they are often not peer reviewed.
I4 *The study is written in English* Rationale: publications in the field of Computer Science are required to be written and submitted in English	**E4** *The study is not written in English* Rationale: languages other than English do not conform with policies for the submission of articles in the field of Computer Science.
I5 *Full-text is accessible via the VU Library* Rationale: In order to gather the data specified in our data extraction form, we need to access the full-text of the articles. This access has been provided to the researchers via the VU Library system, containing licensing for numerous scientific articles.	**E5** *Full-text is not accessible via the VU Library* Rationale: In this study we will exclude the papers that do match the search string but are not accessible via the VU Library. This includes some articles that required purchase or were otherwise unavailable to reach via the VU Library.

2.4 Data extraction

For all of the selected 116 primary studies we extracted data according to the table below. The data extraction was done manually by the researchers by going through all primary studies and using Google Sheets.

Apart from the metadata used for the demographics of the primary studies, we are interested in the specific Knowledge Areas and Application Domains of the articles. Combining metadata information with the assigned areas of research allows us to present the current state of research in a statistical manner. We want to present the evolution of research over time as well as identify certain trends and patterns in software sustainability related articles. Table presented below presents an overview of the data extracted for each selected primary study, as well as the description of extracted fields.

Table 3: Data extraction form

	Information	**Description**
1	Identifier	Unique identifier associated with each selected study
2	Title	Title of the selected study
3	Author(s)	Author(s) of the selected study
4	Year of Publication	The year in which the selected study was published.
5	Venue	Publication venue (e.g. which conference or journal or workshop…)
6	Publication Type	Journal Article, Conference Article, Book Chapter
7	Software sustainability categorization	Binary value OF/FOR: whether sustainability is mentioned in the context of sustainability OF software itself or using software to achieve (i.e. FOR) sustainability.
8	Knowledge Area	Knowledge Area from SWEBOK
9	Application domain (if applicable)	If mentioned, the domain of application of software sustainability

3. Results

An overview of the search result numbers is given in the Table 4 below. From the initial number of studies we have selected 116 as our primary studies. We will use these studies to extract the data and answer our research questions.

Table 4: Overview of the search result numbers

Search results	1584
After removing duplicates	1365
After removing papers that did not match search string	425
After exclusion round based on paper title	245
After 45 random exclusions	200
Primary studies	116

RQ1 How does the research done on sustainability of software compare to the research on software to achieve sustainability?

Earlier in this paper, we have presented our interpretation of software sustainability that involves either using software to achieve sustainability (FOR) or sustainability of software (OF) itself. In Table 5 we have classified each of the primary studies according to their sustainability focus. From this table we can observe that the number of studies focused on *sustainability of software* itself is more than twice as big as the number of studies focused on *software to achieve sustainability*. We believe that researchers are currently focusing on defining and researching various aspects of software sustainability.

Table 5: Amount of studies per interpretation of Software Sustainability

FOR	34
OF	75
BOTH	5

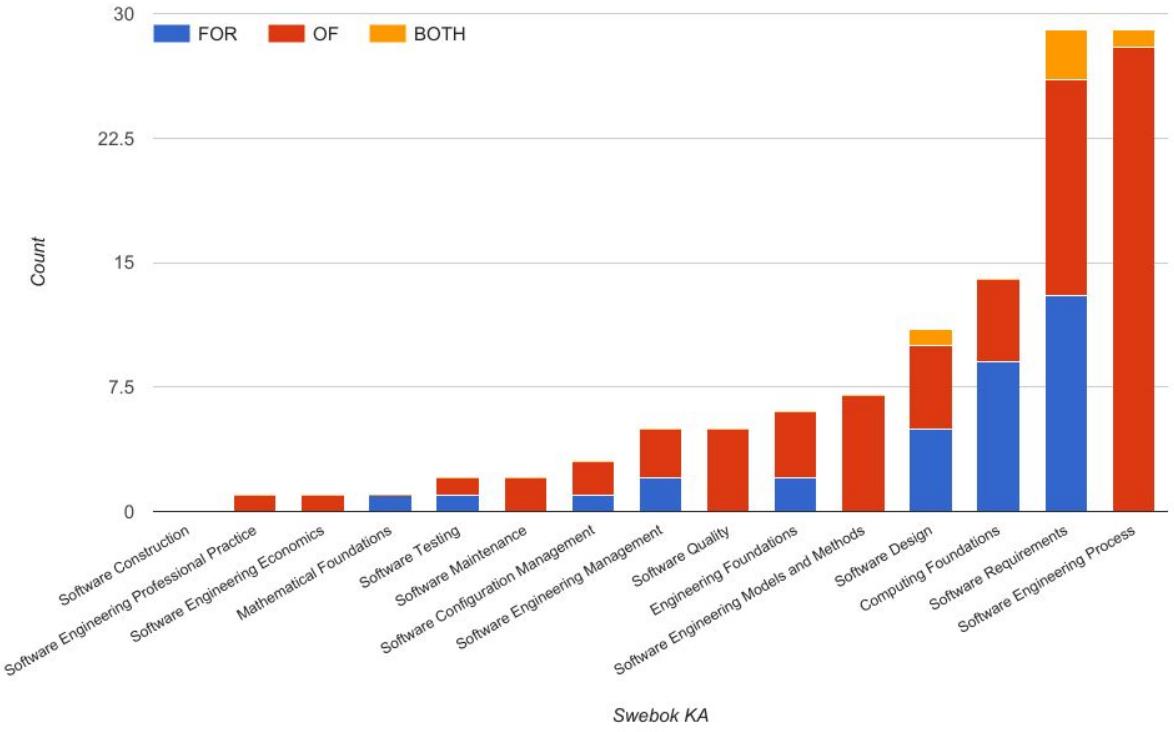
RQ2 What research topics are being addressed?

Figure 1 depicts the amount of primary studies per Swebok Knowledge Area. The colors depict the distribution of articles focused on sustainability of software and software for sustainability. We find that 29 articles are published on both Software Requirements and Software Engineering Process, the highest amount.

For Software Requirements, there are two reasons for this high number. First, many papers propose some new software tool, which we classified under Software Requirements as they outline the requirements for the new software. These papers are also the reason for the high amount of papers that are classified as sustainability FOR software under this knowledge area. Second, researchers in this emerging field are trying to define software sustainability and the factors that influence the sustainability of software. This type of research often leads to some preliminary requirements or factors that developers should consider during the requirements phase.

For Software Engineering Process, the reason for the high number of papers in this Knowledge Area is because a lot of research is done on measuring the sustainability of *existing* software in different stages of the software lifecycle. Software Measuring falls under the Software Engineering Process Knowledge Area.

Figure 1: Primary studies per Swebok KA



RQ3 How have these research topics evolved over time?

In figure 2, the distribution of the primary studies over time is depicted. The amount of articles published on software sustainability increases over time. This was expected, as the discussion on sustainability in general has become more and more prevalent over the last decade, which in turn poses questions on how software can contribute to sustainability or should be adapted to be more sustainable. The decrease in published articles between 2015 and 2016 might be because not all articles from 2016 were indexed on the search engines at the time of executing the search.

Figure 2: Primary studies per year

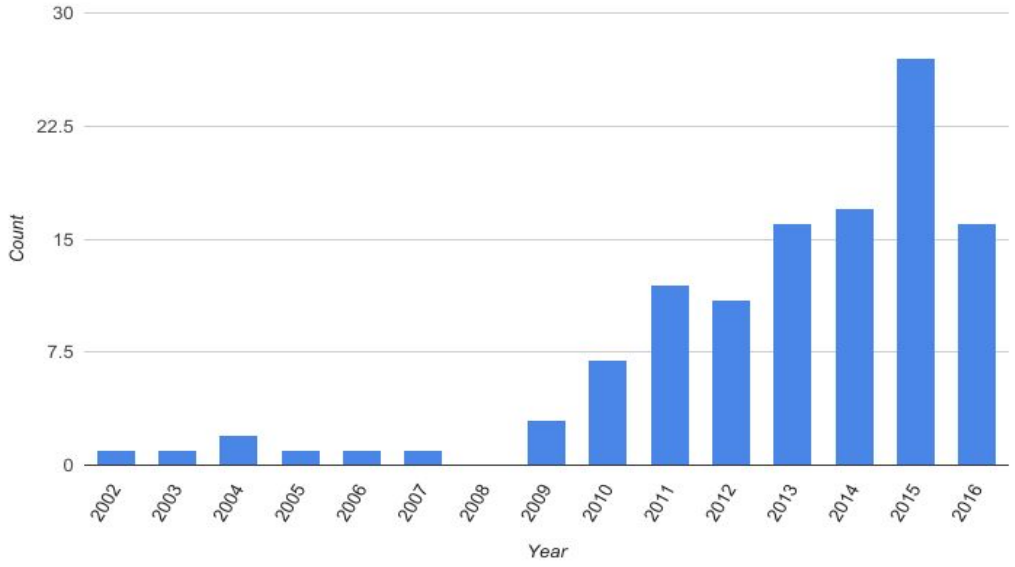


Table 6 depicts the amount of primary studies per SWEBOK Knowledge Area over time. We see that until 2009, most research in the field of Software Sustainability was done in the knowledge areas Software Requirements and Software Design. From 2009 onwards, articles start being published in other Knowledge Areas. Most notable is a large increase in articles in Software Engineering Process.

For some Knowledge Areas, the first articles are only published recently. For example, the first articles published in Software Configuration Management, Software Maintenance and Software Quality are as recent as 2015.

Table 6: Primary studies per SWEBOK Knowledge Areas over time

SWEBOK Knowledge Area	'02	'03	'04	'05	'06	'07	'08	'09	'10	'11	'12	'13	'14	'15	'16
Software Requirements	1		1			1				3	1	5	4	1	3
Software Design			1	1						2	1	1	2	1	2
Software Construction															
Software Testing									1					1	
Software Maintenance														2	
Software Configuration Management														2	1
Software Engineering Management										1			2	2	
Software Engineering Process		1						1	4	3	6	5	5	4	
Software Engineering Models and Methods									1	1		2	1		2
Software Quality														2	3
Software Engineering Professional Practice											1				
Software Engineering Economics															1
Computing Foundations								1		1	1	2	2	3	4
Mathematical Foundations					1										
Engineering Foundations								1	1	1	1	1	1		

RQ4 Which application domains have been considered?

For our selection of primary studies we investigated the practical application domains mentioned in the papers. Around half of the papers were focusing on a broader application of sustainability and were not related to a specific application domain, however out of our selection of 116 primary studies, we have been able to extract 53 articles with defined practical application domains. The process of assigning application domains was done manually by both researchers.

From the 53 papers that contain a specific application domain, 28 of them were focused on using software to achieve sustainability (FOR), 23 were focused on sustainability of software (OF) and 2 articles were focused on both fields.

Papers containing a specific practical application cover a wide range of different fields of study and expertise. In order to gain some insightful information, we have constructed a word cloud containing the mentioned assigned application domain. For this, we have used a publicly available free tool found[1]. The outputs from the word cloud are given below.

[1] http://www.wordclouds.com/

Most commonly mentioned practical application domains revolved around software sustainability in the domain of Networking. Furthermore, popular application domains involved Green Construction, High Performance Computing (HPC) and Sustainability Management areas.

Networking application domains cover the fields of Server and Data Center management, Cellular and Radio networking systems as well as Networking Systems engineering. The reason for networking domain being the most commonly mentioned is due to the fact that networking technologies nowadays have very high energy consumption profiles. Therefore we can reason that this domain attracted the most popularity among researchers, seeing as there is space for improvement in the field of sustainability. Papers with application domain in Networking mostly focused on improving software sustainability of software-defined radio networks, sustainability measurements of energy consumption of various server and data-management systems and algorithms to increase energy efficiency of networking technologies such as routers or switches.

High-Performance Computing domain is related to Networking in the sense of high energy consumption. In our research we came across a few papers that had their application in this field. Research papers in this field present novel ways of improving energy efficiency of HPC components

and systems. Focus of these papers is on increasing sustainability while maintaining the desired high performance. Another domain gaining popularity is related to increasing sustainability of architecture. Papers in this domain demonstrate the usage of various simulation tools that help architects in designing 'greener' buildings or managing urban areas.

4. Threats to validity

In this section we discuss the threats to the validity of this study, posed by the study design.

Exclusion of Web of Science

Our preliminary search results led us to discard Web of Science articles due to various reasons. Firstly, we have noticed that most of the articles relevant to our study were already indexed by other digital libraries. Furthermore, there have been numerous false positives in the results, where the titles of the articles did not match the search query. Lastly, some of the pre-checked articles proved to be unfit for the study due to their hard accessibility or lack of full-text availability. Therefore, it has been decided to exclude results from Web of Science completely. However, it is possible that this exclusion contained some articles that were relevant for our study and that were not indexed by other digital libraries, therefore excluding them from our results and affecting the correctness of our study.

Random exclusion

After the execution of the second round of exclusions, we were left with 245 articles. Before this round, our expectations were that we will have around a hundred articles remaining for the inclusion round. However, due to lack of resources, it would be unfeasible for two researchers to cover all 245 articles. Therefore we have decided to exclude some articles to lower the number of articles to 200. The exclusion was done randomly on 45 articles to maintain statistical objectivity. This poses a threat to validity since we do not know how relevant or not were the excluded articles.

Search engine correctness

Upon initial results observation, we have noticed some papers were indexed by the search engines that did not match our designated search query (e.g. papers that did not contain the search criteria in the title but rather in abstract or full-text). Therefore, these articles have been excluded automatically. Since some of the results that did not match the search query were included, it is also possible that some of the results that did match the search query were not included, therefore posing a threat to validity of our results.

5. Conclusion

In this paper we have provided a systematic literature review on the current state of research related to software sustainability. We have focused on papers relating to sustainability of software itself and papers related to using software to achieve sustainability. Our research objective was detailed through four research questions related to comparing different sustainability approaches, researched knowledge areas and application domains and the evolution of software sustainability research popularity over time. The research was conducted by two researchers under supervision of an internal reviewer over a course of 4 months.

We found that amount of research done on software sustainability has grown exponentially over the last 15 years, due to the popular discussion on sustainability in general getting more and more popular. Not only the number of articles published has seen rapid growth, we also found a growth of the number of different SWEBOK areas being researched. The most popular knowledge areas, namely Software Requirements and Software Engineering Process suggest that there is a trend in defining new green software requirements in the development of new applications. This is supported by numerous papers presenting methods to measure existing software sustainability.

Regarding practical applications of software sustainability related research, we have found that the most popular domains were Networking and High-Performance Computing. The researchers have focused their attention to these fields due to their high energy consumption nature, therefore trying to improve software sustainability in these fields more than others. However, there is also a growing interest in the field of architecture, where software is used to increase sustainability of urban areas.

In the section below we present a summary of the conclusions drawn at the end of our research, given as answers to our earlier presented research questions.

RQ1 From our distinction of software sustainability interpretation mentioned earlier in this paper, we have concluded that the current research focus is on the sustainability OF software related topics.

RQ2 Our list of selected primary studies was classified into SWEBOK [3] Knowledge Areas. From this classification we have been able to conclude that the research done has been mostly addressing research topics in the fields of Software Requirements and Software Engineering Process, however other Knowledge Areas have started gaining popularity in the recent years.

RQ3 Research evolution on software sustainability over time has been steadily growing in the past decade, with the most noticeable increase in popularity noticed in 2009.

RQ4 From the papers that were considering a specific practical application domain, most popular domains were Networking and HPC.

Finally, looking forward, we expect a continuing growth in research on Software Sustainability. With preserving the environment and fighting global warming being one of the biggest challenges mankind faces in the next decennia, and on top of that software becoming more and more part of our everyday lives, it is to be expected that research on the intersection of these topics will also keep increasing.

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