Sustainability in Software Engineering: 
A Systematic Literature Review

Abstract—Background: Supporting sustainability in software engineering is becoming an active area of research. We want to contribute the first Systematic Literature Review (SLR) in this field to aid researchers who are motivated to contribute to that topic by providing a body of knowledge as starting point, because we know from own experience, this search can be tedious and time consuming.

Aim: We aim to provide an overview of different aspects of sustainability in software engineering research with regard to research activity, investigated topics, identified limitations, proposed approaches, used methods, available studies, and considered domains.

Method: The applied method is a SLR in five reliable and commonly-used databases according to the (quasi-standard) protocol by Kitchenham et al. [1]. We assessed the 100 first results of each database ordered by relevance with respect to the search query.

Results: Of 500 classified publications, we regard 96 as relevant for our research questions. We sketch a taxonomy of their topics and domains, and provide lists of used methods and proposed approaches. Most of the excluded publications were ruled out because of an unfitting usage of terms within the search query.

Conclusions: Currently, there is little research coverage on the different aspects of sustainability in software engineering while other disciplines are already more active. Future work includes extending the study by reviewing a higher number of publications, including dedicated journal and workshop searches, and snowballing.

I. Motivation and Background

Sustainability is currently an omni-present term in calls for research proposals and conference sessions (ICSE, CAiSE, RE, etc.). However, in literature, there is no overview of the current state of the art in supporting sustainability in software engineering research and practice. Consequently, researchers who are motivated to contribute to that topic (like the first author [2]) have to invest much time in finding a basic body of knowledge through literature research of many unrelated leads.

This paper reports on our systematic literature review with the objective of retrieving a solid basis of knowledge on the support of sustainability in software engineering. The full protocol is available online as technical report [4].

A. Definition of Sustainability

To clarify our research objective, we define our understanding of sustainability and what we mean by sustainability and how we want to apply it to software engineering. The most cited definition of sustainable development [5] is to “meet the needs of the present without compromising the ability of future generations to satisfy their own needs.” According to [5], sustainable development needs to satisfy the requirements of the three dimensions of society, economy, and environment. A fourth dimension, human sustainability, is less present in the public discussion. According to [6], it should be included, as it is the basis for the other dimensions. All four dimensions of sustainability are further detailed on in our SLR protocol [4].

B. Sustainability Aspects in Software Engineering

Sustainability aspects can be brought to bear both during the development and use of software systems. We distinguish four aspects of sustainability in SE (orthogonal to the dimensions introduced in Sec. I-A). The development process viewpoint includes:

- Development process aspect: Sustainability in the initial system development process (with responsible use of ecological, human, and financial resources). This aspect focusses on the initial conceptual and constructional development and we distinguish it from the late phase of actual system production for reasons of analysis.

- Maintenance process aspect: Sustainability of the software system during its maintenance period until replacement by a new system (with continuous monitoring of quality, knowledge management).

The product viewpoint encompasses the aspects of sustainability during production and usage:

- System production aspect: Sustainability of the software system as product with respect to its use of resources for production (using green IT principles and sustainably produced hardware components). The actual system production happens after most of the initial development process and considers, inter alia, mass production aspects, logistics and factory organization issues.
- **System usage aspect:** Sustainability in the usage processes in the application domain triggered by the software system as product (responsible in impact on environment, using green business processes).

We expect these aspects to have different scales of impact, growing from small to large in the order presented above, so that the system usage aspect potentially has the biggest impact (and, therefore, improvement potential). However, this is also dependent of the system under analysis.

For our SLR, we are looking for all four aspects of sustainability in software engineering. The aspects imply different levels of abstraction and varied granularity, but nevertheless we are interested in the state of research for each of them.

C. A Body of Knowledge for Sustainability in SE

Our research aim for the next years is to support the development of ICT systems for environmental sustainability (ICT4ES) with an adequate software engineering approach that integrates the knowledge of related disciplines that are concerned with sustainability. For that we need to build up on existing knowledge is SE as well as disciplines that have been related closer to sustainability, for example, environmental informatics.

This research aim requires accumulating a body of knowledge for various reasons: justifying the basis for future research, learning as much as possible from other domains related to the topic, and providing a basis for other researchers as well as students who consider learning about and contributing to this area. One commonly accepted research method for accumulating a body of knowledge is a study in form of a systematic literature review.

D. Research Questions

The overall research objective of the study is to find out what the current state of the art in supporting sustainability in software engineering research and practice is. This is further detailed in the following research questions:

- **RQ1** How much activity was there in the last 20 years?
- **RQ2** What research topics are being addressed?
- **RQ3** What are the limitations of current research?
- **RQ4** How is sustainability support performed?
- **RQ5** Which methods are in use?
- **RQ6** Are there case studies available?
- **RQ7** Which domains are already considered?

E. Related Work

There are systematic literature reviews on different topics in software engineering, but so far none has been conducted that investigates the relation between sustainability and software engineering.

Mahaux et al. [7] performed a preliminary search on the DBLP Computer Science Bibliography database [4] for articles with the prefixes “sustainab-” OR “ecolog-” OR “environmental-” in the title, the data base returned over 3000 results (in January 2010), but filtering on important software-related venues lead to as few as 11 results. They propose that a systematic literature review should be conducted.

In contrast to [7], we are interested in publications from all scientifically sound venues and journals as we see great potential for learning from other domains. Therefore, we did not restrict this systematic literature review to software-related venues, which is the main reason why we received more results.

II. Search Design and Process

The search design and procedure follow the guidelines in [11]. As SLR research questions we directly adopted those enumerated in Sec. [10]. The search process for this study is based on an automated search of the following digital libraries:

- ACM Digital Library [http://dl.acm.org]
- SpringerLink [www.springerlink.com]
- ScienceDirect / Scopus [http://www.sciencedirect.com]
- Web of science [http://apps.webofknowledge.com/WOS]

A. Search String

The aim for our search string is to capture all results that relate sustainability or environmental issues with software engineering or requirements for software systems. The reasons for searching for requirements is that in this early development phase sustainability issues should emerge. The search string used on all databases is:

\[
(sustainab* \text{ OR environment* OR ecolog* OR green})
\]

AND

\[
(software \text{ engineering OR requirement OR software system})
\]

Although we explicitly list keywords in our search string that rather point to environmental sustainability, we expect to find all dimensions of sustainability.

B. Inclusion Criteria

We chose the following inclusion criteria in order to select the relevant publications to answer our research questions:

- Publication date between 1/1/1991 - 31/12/2011
- Requirements phase of software development process
- Explicit mentioning of software engineering
- Scientific soundness
- Relevance with respect to research questions
- Analysis of sustainability-relevant application domains
- Coverage of a SW ecosystem or SW sustainability

2Our hypothesis is that most publications will be much younger, so a time span of 20 years ensures that we include all relevant ones.
C. Exclusion Criteria

- “Environment” used in the sense of system environment, not nature.
- “Ecosystem” used as population of interacting systems, for example, agents.

D. Roles and Responsibilities

- Birgit Penzenstadler (TUM, principal researcher): IEEE-EXPlore, result classification, detailed analysis
- Zolboo Ochirsukh, Elena Mircheva, Duc Tien Vu, Tuan Duc Nguyen (TUM, student research assistants): search on ACM, Web of Science, ScienceDirect, SpringerLink
- Veronika Bauer (TUM, expert reviewer): assessment of search result classification, review of detailed analysis
- Coral Calero (UCLM, expert reviewer): assessment of search result classification and detailed analysis
- Xavier Franch (UPC, expert reviewer): review of detailed analysis

E. Article Selection Process

The process was conducted as follows:
1) The researchers execute the search on each database and save the references in bibliography files.
2) The principal researcher reads all titles and abstracts and checks the inclusion and exclusion criteria for each entry. Major criterion is the topic of the content.
3) The principal researcher classifies the papers and articles according to type, topic, and domain.
4) The expert reviewers reassess the classification and inclusion/exclusion of search results. After their reassessment, we introduce an additional result classification: domain-specific papers that are interesting to learn from but not focussed on software engineering.
5) The principal researcher extracts statistics and analyses the included results in further detail. This is followed by a second classification from the expert reviewers.

F. Data Analysis

The data is tabulated to show:
- The data and numbers of query results. (RQ1)
- Listed by database for included publications:
  - Author, reference, date (RQ1)
  - Publication type and type of content (RQ6)
  - Topic of content (RQ2, RQ4, RQ5)
  - Application domain (RQ7)
  - Benefit for our body of knowledge (RQ4)
- The number of relevant publications per year. (RQ1)
- The respective venues and journals. (RQ1)

Furthermore, the findings for RQ3, RQ4 and RQ5 are reported on separately. Due to the limitation of space, we provide the full list of references of the primary study as online appendix [8].

III. RESULTS

The overall number of results for each data base is listed in Tab. I.

Table I

<table>
<thead>
<tr>
<th>Database</th>
<th>Date</th>
<th>Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>IEEE Xplore</td>
<td>27/12/11</td>
<td>319.601</td>
</tr>
<tr>
<td>ACM Digital Library</td>
<td>26/12/11</td>
<td>104.217</td>
</tr>
<tr>
<td>SpringerLink</td>
<td>29/12/11</td>
<td>500.004</td>
</tr>
<tr>
<td>ScienceDirect / Scopus</td>
<td>29/12/11</td>
<td>10.749</td>
</tr>
<tr>
<td>Web of Science</td>
<td>29/12/11</td>
<td>80.503</td>
</tr>
</tbody>
</table>

All results were ordered “by relevance” as displayed by the databases. From these results, we considered the first 100 results of each data base in our first iteration of the study. In total, we reviewed 500 publications.

The following abbreviations are used to categorize the results in Tab. II-VI:

- **Publication**: Kind of publication, e.g., Journal Article (A), Conference Paper (CP), Workshop Paper (WP), Book Chapter (BC), Letter to the editor (L)
- **Type**: Kind of content presented in the publication, e.g., method, experience report, empirical study, tool
- **Topic**: Short hint on principal content and keywords of the paper or article
- **Domain**: Application or technology domain considered in the publication, e.g. transport, aviation, embedded systems, information systems, human aspects
- **Benefit**: Classification of why we consider this publication to be relevant with respect to the research questions: Sustainability in software engineering (S in SE), sustainability-related application domains (S App Dom), sustainability (modeling) concept (S Concept), sustainable software solutions (S SW Sol), sustainable hardware solutions (S HW Sol)

RQ1: How much activity was there in the last 20 years?

We summarized the number of relevant publications per database in Tab. VII per year in Tab. VIII and per publication type in Tab. IX. In the last two years, there was a significant increase in the number of publications, and there was no publication included that was older than 2005, so our hypothesis for RQ1 holds. None of the results we included are older than 2005, but we did have older search results in the query evaluations, so this is not due to restricted availability online. Although we executed the search queries in late December, we already found journal articles dated to January 2012 in the results which we included as they were fully available.

While the venues were relatively distributed, there was an accumulation of publications from “Environmental Modeling & Software” as well as the “Journal of Cleaner Production”. The fact that we classified many of the publications as “software solutions” or “sustainability-related application...
domain", some more as “sustainability concepts” and only few as “sustainability in software engineering” implies that there is still relatively little research published that could be considered for building up a body of knowledge.

**Table VII**
INCLUDED RESULTS PER DATABASE

<table>
<thead>
<tr>
<th>Name</th>
<th>Number of Included Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>IEEEExplore</td>
<td>5 out of 100</td>
</tr>
<tr>
<td>ACM Digital Library</td>
<td>32 out of 100</td>
</tr>
<tr>
<td>Springer Link</td>
<td>5 out of 100</td>
</tr>
<tr>
<td>Science Direct</td>
<td>30 out of 100</td>
</tr>
<tr>
<td>Web of Science</td>
<td>24 out of 100</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>96 out of 500</strong></td>
</tr>
</tbody>
</table>

**Table VIII**
INCLUDED RESULTS PER YEAR

<table>
<thead>
<tr>
<th>Year</th>
<th>Number of Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>1991 - 2005</td>
<td>0</td>
</tr>
<tr>
<td>2006</td>
<td>9</td>
</tr>
<tr>
<td>2007</td>
<td>12</td>
</tr>
<tr>
<td>2008</td>
<td>11</td>
</tr>
<tr>
<td>2009</td>
<td>11</td>
</tr>
<tr>
<td>2010</td>
<td>21</td>
</tr>
<tr>
<td>2011</td>
<td>29</td>
</tr>
<tr>
<td>2012</td>
<td>3</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>96</strong></td>
</tr>
</tbody>
</table>

**Table IX**
INCLUDED RESULTS PER PUBLICATION TYPE

<table>
<thead>
<tr>
<th>Publication Type</th>
<th>Number of Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>Journal articles</td>
<td>65</td>
</tr>
<tr>
<td>Book chapters</td>
<td>2</td>
</tr>
<tr>
<td>Conference papers</td>
<td>27</td>
</tr>
<tr>
<td>Workshop papers</td>
<td>1</td>
</tr>
<tr>
<td>Letters to the editor</td>
<td>1</td>
</tr>
<tr>
<td>Technical reports</td>
<td>0</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>96</strong></td>
</tr>
</tbody>
</table>

**RQ2: What research topics are being addressed?**

For a quick illustrated overview, we have generated a weighted topic cloud from keywords, taken from the titles and abstracts, that visualizes the topics in Fig. 1. We have derived a taxonomy for the addressed research topics in Fig. 2 that abstracts from some of the details listed in the original classifications tables in Tab. [IV]. The dimensions of the taxonomy are the degree of domain specificity, from general purpose to domain-specific research and the indexing between analytical approaches (frameworks and assessment) and constructive approaches (methods and tools). The taxonomy shows a tendency towards domain-specific, constructive approaches. There are not many publications rated as general purpose, and there is little methodical guidance for supporting sustainability.

Both the keyword cloud and taxonomy rely strictly on keywords taken from titles and abstracts. Nevertheless, their reproduction might reveal slightly varied results, but we do not consider that a problem as we use them only to give an overview of topics without deriving any further statistics from them.

**RQ3: What are the limitations of current research?**

To identify limitations of current research, we reviewed our classification of topics and application domains in Tab. [IV]. We performed a pragmatic and informal gap analysis that resulted in three major limitations:

- **High complexity.**

  Reason: Due to the high connectivity between the different aspects of sustainability, (software) systems engineering becomes highly complex. This is visible in knowledge management approaches, e.g., [9] and decision support systems, e.g., [10].

  Conclusion: High complexity requires clear concept definitions and consistent, traceable models. One method to cope with high system complexity that might prove helpful is systems’ thinking [11].
• High domain-specificity.
  Reason: The frameworks and methods we found within the results are highly domain-specific, e.g., [12], [13]. This is also visible in the higher density of domain-specific approaches in Fig. 2.
  Conclusion: Effective approaches for supporting sustainability require specific domain knowledge.
• Software engineering.
  Reason: There is only one approach in software engineering that explicitly addresses sustainability. It is a reference framework with specific application in web engineering [14].
  Conclusion: An encompassing reference framework for SE is still missing.

RQ4: How is sustainability support performed?

  Constructive support for sustainability is performed by frameworks, models, methods, and metrics (Tab. X). Thereby, most approaches are specific to a special application domain, as visible by the density on the domain-specific side in Fig. 2.
  • Frameworks, e.g., for civil engineering [12] or contaminant transport [15].
We have derived a taxonomy for the domains that were used and described in the publications in Fig. 4. We used the same dimensions as for the research topics taxonomy in Fig. 2 and identified five coarse-grained domain clusters: Systems & Knowledge in the area of general purpose, analytical approaches, Technologies & Methods on the constructive side of the general purpose dimension, Education somewhere in the middle between these two, special Disciplines provide more domain-specific, analytical approaches, and the corresponding Application & Implementation cluster contributes the domain-specific, constructive approaches. These clusters are not overlap-free, but only a means to illustratively structure their diversity. The terms within the cluster clouds in Fig. 4 indicate the individual domains.

IV. DISCUSSION

A. Conclusions on the State of the Art

We started our search expecting to find more results to be classified as Sustainability in Software Engineering (S in SE in column Benefit in Tab. II–VI). As we found less than expected for a body of knowledge on S in SE, we decided to extend the inclusion to publications that we classified as a research we could learn from when further investigating sustainability in software engineering. This lead to the other Benefit categories S Concept, S App Dom, S SW Sol, and S HW Sol as explained in Sec. III.

In our opinion, there is still a lot of research work to be done, especially to support the different dimensions of sustainability from within the software engineering discipline. This can either occur in form of domain-independent guidelines or domain-specific methods.

B. Conclusions for a Body of Knowledge

Due to these findings, our envisioned Body of Knowledge has areas that represent the core S in SE publications, plus areas that represent application domains with software and hardware solutions as well as sustainability concepts from related disciplines that we can learn from. This is illustrated in Fig. 5.

![Figure 5. Areas of the Body of Knowledge for S in SE](image-url)
## Table XI
### Case Studies

<table>
<thead>
<tr>
<th>Author and ref.</th>
<th>Domain</th>
<th>Context</th>
<th>Applied method</th>
</tr>
</thead>
<tbody>
<tr>
<td>Huang et al. [10]</td>
<td>web engineering</td>
<td>support green customers’ decision process on electronic commerce</td>
<td>questionnaire and experiment</td>
</tr>
<tr>
<td>Faith-El et al. [11]</td>
<td>cleaner production</td>
<td>application of environmental requirements in Swedish road maintenance</td>
<td></td>
</tr>
<tr>
<td>Liu et al. [23]</td>
<td>energy</td>
<td>energy requirements and carbon dioxide emissions of tourism industry</td>
<td></td>
</tr>
<tr>
<td>Tseng et al. [24]</td>
<td>cleaner production</td>
<td>evaluating a firm’s green supply chain management</td>
<td></td>
</tr>
<tr>
<td>Yen et al. [25]</td>
<td>business research</td>
<td>management’s role in adopting green purchasing standards in industry</td>
<td></td>
</tr>
<tr>
<td>Zhang et al. [26], [27]</td>
<td>property development</td>
<td>costs and barriers of green property development in China</td>
<td></td>
</tr>
<tr>
<td>Jia et al. [28]</td>
<td>ecology</td>
<td>urban wetland planning in Beijing</td>
<td>ecological complexity research</td>
</tr>
<tr>
<td>Jin et al. [29]</td>
<td>hydrology</td>
<td>ecological water demand for basin systems</td>
<td>integrated calculation</td>
</tr>
</tbody>
</table>

Figure 3. Weighted domain cloud, created with [http://www.wordle.net/](http://www.wordle.net/)

Figure 4. Taxonomy of application domains
C. Threats to Validity

There is a number of threats to validity that we are aware of and tried to minimize by different mitigation actions.

1) Researcher’s bias: The semi-automatic part of the search was performed by five researchers. There could be a researcher’s bias as the first selection was performed by only one researcher. We minimized the effects of such a bias by two measures:

- We explicitly stated the research questions, inclusion and exclusion criteria, and the rationale for performing the search.
- The first selection was reviewed and assessed by two expert reviewers from different institutions (TUM, UCLM). Differences were subsequently discussed, resolved and commonly agreed upon.
- The detailed analysis of the principle researcher was reviewed by all three expert reviewers (TUM, UCLM, UPC).

2) Search string validity: The search string validity can be questioned under two aspects: On one hand whether it filtered out too many publications that would have been relevant, and on the other hand whether it included too many irrelevant results and was, in either case, not the adequate search string.

Indicators for too many false positives are purely hardware papers, but as the automatically found Green IT publications all contained part of the second parenthesis of the search string, they were included in the results. Then, purely application in environmental domains, for example, agricultural support systems with no explicit relation to sustainability but relevant in case they exhibited an explicit link to sustainability in their content. Furthermore, “environment” used in the sense of system environment, not nature — these samples had to be excluded by hand as well as “ecosystem” used as population of interacting systems, for example, agents.

Indicators for too many relevant exclusions were that we found less relevant results than we would have expected. This can either be due to a search string that was too restrictive, to a search that was not extensive enough, or to the fact that there is rather little published yet on that specific topic. Not all publications we would have expected showed up early in the search results. For example, we missed Cabot et al. [30], as they treat goal modeling for supporting sustainability in the context of conference organisation. Mahaux et al. [7] were also missing in the results, with their work on exploring sustainability requirements.

3) Database query evaluation: We did not have any information on which database performed which kind of search query evaluation, and a lazy versus an eager database query evaluation of the search string would probably have a significant impact on the search results, considering that we reviewed the first 100 most relevant results.

In case of a “lazy” search string evaluation, the results might have included more references matching early parts of the search string than compared to matching later parts. In that case, the results might be slightly biased in terms of favoring the terms “sustainability” and “software engineering” and subordinating “green” and “software systems”.

As many of the results contained the term “software system” and not “software engineering”, we are confident that there was no bias introduced by database query evaluation.

4) Cross-validation of the search engines: We received hardly any double entries in the automatic search results. We would have expected some double entries in the more general databases ScienceDirect and WebOfScience. We decided not to use meta search engines in our first iteration of the SLR because relying on only one meta search engine would have made us completely dependent of the reliability of that engine, and using various meta search engines would have led to highly redundant results, as a pre-check showed.

Interestingly, Web of Science found Estrin [31] highly ranked, which originates from IEEEExplore but was not included in the IEEEExplore results (at least not within the first 100 results). This might be a hint towards different search query evaluation.

It would be one interesting step in future work to replicate the searches on more databases and meta search engines and explicitly compare the coverage.

V. Conclusions

In this paper, we presented the results of our SLR [4] on the research activity in sustainability in software engineering and related topics that allow for building up a body of knowledge. We considered 96 of 500 reviewed publications relevant with respect to our research questions and classified them according to content, topic, application domain, and potential benefit for further investigation. On that basis, we provided taxonomies for represented research topics and application domains. As there were not as many publications explicitly presenting work on sustainability in software engineering than expected, we propose an extended body of knowledge for S in SE that includes related application domains and sustainability concepts from related disciplines that we can learn from when further investigating S in SE.

Future work is to extend the study in two directions: on one hand by snowballing (following references) and on the other hand via meta search engines, book search engines, and dedicated journal searches. Probably even more important is the challenge of making SLRs themselves “sustainable” by providing yearly updates that not only repeat an SLR but adapt the iterations over the years according to lessons learned from previous iterations. Thereby, we can establish stable bodies of knowledge.

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4These works were not included into the results manually because we wanted to strictly follow the SLR method. However, they will be included in the extended version and the envisioned body of knowledge.
REFERENCES


