Systematic Mapping Study on Software Engineering for Sustainability (SE4S)

Birgit Penzenstadler, Ankita Raturi, Debra Richardson
University of California, Irvine
{bpenzens|araturi|djr}@uci.edu

Coral Calero
Universidad de Castilla - La Mancha, Spain
coral.calero@uclm.es

Henning Femmer
Technische Universität München
femmer@in.tum.de

Xavier Franch
Universitat Politècnica de Catalunya, Spain
franch@essi.upc.edu

ABSTRACT

Background/Context: The objective of achieving higher sustainability in our lifestyles by information and communication technology has lead to a plethora of research activities in related fields. Consequently, Software Engineering for Sustainability (SE4S) has developed as an active area of research. *Objective/Aim*: Though SE4S gained much attention over the past few years and has resulted in a number of contributions, there is only one rigorous survey of the field. We follow up on this systematic mapping study from 2012 with a more in-depth overview of the status of research, as most work has been conducted in the last 4 years. *Method*: The applied method is a systematic mapping study through which we investigate which contributions were made, which knowledge areas are most explored, and which research type facets have been used, to distill a common understanding of the state-of-the-art in SE4S. *Results*: We contribute an overview of current research topics and trends, and their distribution according to the research type facet and the application domains. Furthermore, we aggregate the topics into clusters and list proposed and used methods, frameworks, and tools. *Conclusion*: The research map shows that impact currently is limited to few knowledge areas and there is need for a future roadmap to fill the gaps.

Categories and Subject Descriptors

D.2.1 [**Software Engineering**]: [Requirements, Methodologies]

Keywords

Sustainability, Software Engineering, Systematic Mapping Study

EASE'14, May 13 - 14 2014, London, England, BC, United Kingdom

http://dx.doi.org/10.1145/2601248.2601256 ...$15.00.

1. MOTIVATION & BACKGROUND

Over the last decades, sustainability research has emerged as an interdisciplinary area; knowledge about how to achieve sustainable development has grown, while political action towards the goal is still in its infancy [1].

A sustainable world is broadly defined as "one in which humans can survive without jeopardizing the continued survival of future generations of humans in a healthy environment" [2]. This anthropocentric view of sustainability allows us to consider the implications of, and necessities for, human existence in the world.

Sustainability can be also discussed with reference to a concrete system—such as an ecological system, a human network, or a specific software system. Here, global sustainability implies the capacity for endurance given the functioning of all these systems in concert. Software Engineering for Sustainability has developed as a current focus of research as a result of software engineers engaging in issues regarding the impact of software systems on global sustainability.

Definition The term *Sustainable Software* can be interpreted in two ways: (1) the software *code* being sustainable, agnostic of purpose, or (2) the software *purpose* being to support sustainability goals, i.e. improving the sustainability of humankind on our planet. Ideally, both interpretations coincide in a software system that contributes to more sustainable living. Therefore, in our context, sustainable software is energy-efficient, minimizes the environmental impact of the processes it supports, and has a positive impact on social and/or economic sustainability (1 & 2). These impacts can occur direct (energy), indirect (mitigated by service) or as rebound effect [3]. The aim of Software Engineering for Sustainability (SE4S) is to make use of methods and tools in order to achieve this notion of sustainable software.

Motivation There is a plethora of (new) journals, conferences and workshops where the topic pops up, so it is hard to get a comprehensive overview of the state of research. There is only one earlier systematic mapping study on sustainability in software engineering, namely the study performed by a subset of the authors of the work at hand from 2012. This first review [4] is now extended and analyzed in more depth and detail, as the first study did not differentiate research facets and knowledge areas. Furthermore, the first study revealed that only very few topics were in the actual area of software engineering, which is why the study then included related research on sustainable software systems outside of software engineering. As the topic has been researched very actively in the past few years, this second study leads to a larger set of data points that allow to draw more conclusions.

Research Objective Our aim is to provide an overview of the current state of research on software engineering for sustainability. The first step was our previous work with an earlier study on the available research [4], and now a related effort is made after only two years because the field has substantially evolved since then.

Contribution We contribute a systematic mapping study that follows the guidelines in [5]. It takes into account the lessons learned from the previous study [4] by defining more robust research questions, using an adapted search string, and including a number of publication channels (journals, conferences and workshops) on the topic that have either been just recently established or were not indexed yet in the earlier study.

2. STUDY DESIGN

We describe the study design in terms of research questions, set-up, and conducted procedures.

Research Questions (Scope).

The overall research objective of the study is to give an overview of the current state of the art in supporting sustainability in software engineering research and practice. This is detailed in the following research questions:

RQ1 What research topics are being addressed?
RQ2 How have these research topics evolved over time?
RQ3 How is sustainability support performed (e.g., models and methods)?
RQ4 Which of those models and methods are used in practice?
RQ5 Which research type facets have been considered in the contributions?
RQ6 Which application domains have been considered?
RQ7 Which research groups are most active and what is the distribution between academics and practitioners?

Roles & Responsibilities.

The roles and responsibilities for this project are defined in Tab. 1. We have two principal researchers (Birgit Penzenstadler and Ankita Raturi), three supporting researchers (Henning Femmer, Coral Calero, Xavier Franch), one internal reviewer (Debra Richardson) and two external reviewers (Daniel Méndez Férnandez and Marcela Genero).

Table 1: Roles and Responsibilities

	BP	AR	DR	CC	HF	XF	DM	MG
Develop protocol [6]	x							
Define search string	x		x					
Define classification scheme	x							
Define data extraction form	x							
Internal review of protocol			x	x	x	x		
External review of protocol							x	x
Revise protocol	x							
Identify primary research	x	x						
Retrieve primary research	x	x						
Clean from duplicates		x						
Vote on search results	x	x		x	x	x		
Assessment of voting			x					
Data extraction	x	x						
Data synthesis	x	x						
Internal analysis validation			x	x	x	x		
External analysis validation							x	
Complete technical report	x	x						
Write paper for EASE	x	x						
Review of report & paper			x	x	x	x	x	

Search Strategy.

Information Sources. The search process for this study is based on an automated search of the following indexing systems and digital libraries: DBLP, Science Direct, Web Of Science, INSPEC, IEEE Xplore, Springer, ACM, JSTOR, arXiv, Wiley, and Citeseer. Furthermore, we added manual searches on conference and workshop proceedings of 2013, as pretests of the search string have revealed that they did not show up in the search results of the indexing systems: ICT4S'13, GREENS'13, and RE4SuSy'13. The reason for them not being indexed was that it was still too early after their publication, but as we knew of their existence and relevance, we decided to include them in order to have more up-to-date results.

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. Not only in software engineering, but especially during the early phase of requirements engineering sustainability issues should emerge and be discussed, which is the reason for specifically including *requirement* in the search string. The search string[1] used on all databases is:

```
(sustainab* OR ecolog* OR green) AND
(software engineering OR requirement* engineering OR requirement*
specification OR software specification OR system specification)
```

We decided *not* to include "environment*" as alternative for sustainab*, ecolog* or green in the first parenthesis because pretests showed only false positives as it is a term frequently used for denoting the system context, operational context, or business context. The second parenthesis contains the part making it relevant for software engineering and the first parenthesis contains the part that links it to sustainability including synonyms and alternative terms that we know are in use. Although we explicitly list keywords in our search string that point to environmental sustainability, we are interested in all dimensions of sustainability as they are strongly related to each other.

Search Execution. We execute the search on the databases specified earlier. The search string is used to perform the search including the meta data fields *title*, *abstract*, and *keywords*. In case the search returned more than 100 results ordered according to the relevance with regard to the search string, we use the first 100 search results of each database. We retrieve the meta information (full citation and abstract) as well as the full texts. We consolidate the results and clean from duplicates. We provide the primary sources as well as a separate voting sheet per classification assessor in a Dropbox folder.

Study Selection Criteria. We chose the following inclusion criteria to select the relevant publications to answer our research questions: Relevance with respect to research questions, scientific soundness (see quality assessment in Sec. 2), and coverage of a software system (as opposed to pure hardware systems).
Exclusion Criteria are *Environment* used in the sense of sys-

[1]The search string used in the preceding study was `(sustainab* OR environment* OR ecolog* OR green) AND (software engineering OR requirement OR software system)`

tem environment, not nature, and *Ecosystem* used as population of interacting systems, for example, agents.

Study selection procedures.

The process was conducted as follows: The five voters read all titles and abstracts and decide on the inclusion and exclusion for each entry according to the criteria given above. If unsure about an article, they read more of the paper until they are decided. Disagreements among voters are resolved by majority as we chose an uneven number of assessors. This also requires at least 3 out of 5 votes for decision taking. The internal reviewer reassesses the inclusion/exclusion of search results.

Study quality assessment checklists and procedures.

The following assessment checklist has been used to assess the quality of the studies under consideration: Peer-reviewed articles, reporting on background and context, description of research method, report on threats to validity.

For quality assessment, we performed internal and external reviews as also specified in Tab. 1. There were five internal reviews and three external ones. We conducted internal reviews of the protocol, of the voting, of the data extraction and classification, of the analysis and data synthesis, of the report. External reviews were performed of the protocol, of the analysis, of the report.

Data extraction strategy.

The principal researchers classify the studies according to the research type facets [7] and the knowledge area [8], as detailed in the list below. They extract information on topics, methods, frameworks, tools, case studies, and application domains.

The data extraction form captures the following data for each included primary resource:

- Metadata: Authors, Year of publication, Title, Source, Keywords, Research topic, Institution
- SWEBOK [8] knowledge area: Software Engineering Economics, Software Requirements, Software Testing, Software Construction, Software Configuration Management, Computing Foundations, Software Engineering Models and Methods, Software Maintenance, Mathematical Foundations, Software Design, Software Engineering Management, Software Engineering Professional Practice, Engineering Foundations, Software Engineering Process, or Software Quality.
- Research type facets [7]: Philosophical, Exploratory, Solution, Validation, Evaluation, Opinion, or Experience.
- Application domain (if applicable)
- Framework and/or Method (if applicable)
- Tool (if applicable)

Synthesis of the extracted data.

The principal researchers extract statistics and analyse the included results in further detail. They map out the current research. The internal reviewer assesses the analysis results and provides feedback. The external reviewers provide feedback. To conduct the data synthesis, we derived descriptive statistics for maps from the extracted data, performed semantic modeling of research topic clusters, mapped out current work, made timelines with amount of publications according to research topic, research type facet, and knowledge area.

3. RESULTS

An overview of the search result numbers is provided in Tab. 2. The publications that were voted in by the majority of reviewers are listed later in Tab. 4. The 83 resulting publications were published quite across a range of journals, conferences, and workshops and covered a variety of topics, knowledge areas and research types. The full report is available online [6].

Table 2: Overview of the search result numbers

Total number of search results	1278
Total number after duplicate removal	1039
Voted in by at least one reviewer	384
Voted in by majority	83

RQ1: What research topics are being addressed?.

We used a variety of methods to structure and model the research topics of the 83 publications that were voted-in. Fig. 1 shows a simple weighted word cloud that was generated from the publication abstracts. It was created with Tagxedo[2], which used a stemming algorithm to filter the textual input. The goal of this image was to gain a first impression of the topical content of the publications.

Figure 1: Weighted word cloud from the original abstracts of voted-in publications.

The next, more in depth analysis method used is called Topic modeling. This is a method for analyzing large data sets to elicit commonalities, in this case topics, which are clusters of words that frequently occur together in the data [9]. It is a "probabilistic model for uncovering the underlying semantic structure of a document collection" [10]. We utilized the Machine Learning for LanguagE Toolkit (MALLET)[3], that is popularly used for machine learning applications to text, including classification, clustering, natural language

[2] `www.tagxedo.com`
[3] `http://mallet.cs.umass.edu`

processing, and topic modeling. The purpose of performing topic modeling on the dataset (consisting the abstracts of the voted-in publications) was to investigate what the 'hot topics' are in the domain of Software Engineering for Sustainability.

In order to be able to run the dataset through MALLET, we preprocessed the abstracts to be represented as a list of words associated with each publication. The dataset was also imported into MALLET using functionality that removed stop words and took into account basic word stemming. As our dataset of 83 documents was small, we only ran the trainer for 100 iterations. The goal was a qualitative corpus exploration [10], so we chose the top 10 topics for consideration. The modeling of the abstracts resulted in the topic clusters of the future of society, urban architecture and integration, energy efficiency, life cycle assessment, environmental management, smart grids, cloud services, carbon consumption, traffic strategies, and virtualization. Please refer to the complete protocol [6] for the full list of topic cluster keywords and further detailed analysis graphs.

Based on the word content of each abstract, and the output from the MALLET topic model, we were able to relate abstracts to the elicited topics. We pruned each topic down to 6 keywords that were most characteristic of the abstracts that belonged to each topic. Fig. 2 shows the resulting clusters of papers and the topics they belong to. The numbers in this graphic refer to the numbers in Tab. 4.

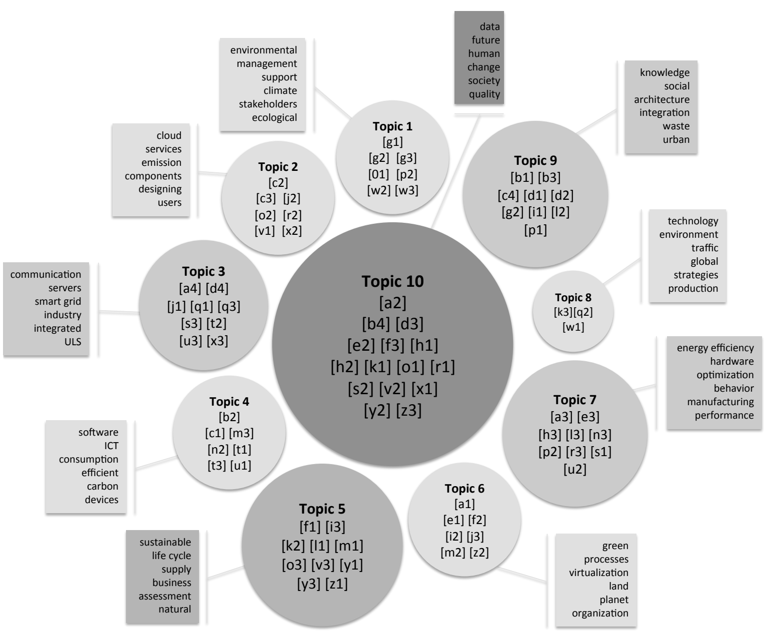

Figure 2: Topic Cluster Modeling of the Abstracts. Numbers in this graphic refer to the numbers in Tab. 4.

During the data extraction phase of this study, we had classified each of the publications under a SWEBOK Knowledge Area [8], as well as under a Research Type Facet as described by [7]. In Fig . 3, we cross reference the Topic Clusters to the Knowledge areas and the Research Type Facets respectively, to allow for the identification of research hotspots.

Popular research in specific Knowledge Areas include: Software Engineering Process regarding Topic 10 [data, future, human, change, society, quality], and Software Design and Software Quality regarding Topic 5 [sustainable, life cycle, supply, business, assessment, natural]. Popular research using specific Research Type Facets include: Solutions research in Topic 3 [communication, servers, smart grid, industry, integrated, ULS], Topic 5 [sustainable, life cycle, supply, business, assessment, natural], Topic 7 [energy efficiency, hardware, optimization, behavior, manufacturing, performance], and Topic 10 [data, future, human, change, society, quality].

RQ2: How have these research topics evolved over time?.

The answer to RQ 2 needs a prelude on how the publications, and therefore our data points, are distributed over time. As depicted in Fig. 4, there were 40 new relevant publications in the last two years alone. A description of the evolution of the topics over time is somewhat limited, as this constitutes a majority of publications that are in domain of Software Engineering for Sustainability.

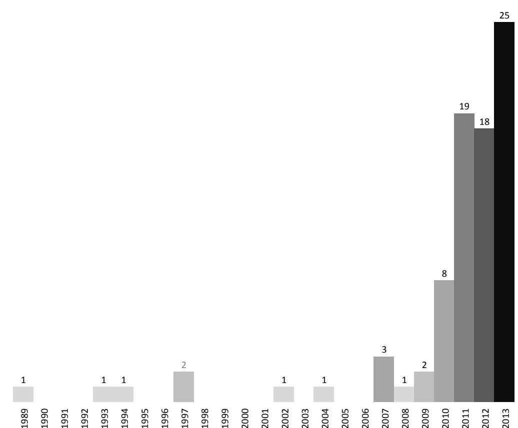

Figure 4: Distribution of the publications over time.

RQ3: How is sustainability support performed?.

There is a wide range of models, methods, frameworks, and tools that are proposed in the publications and used in research. They include standard software engineering support (like goal modeling and service modeling) as well as general purpose methods (like interviews and statistics) as well as more domain-specific methods from systems engineering (life cycle assessment), geosciences (global position system) and the energy domain (measuring devices).

- Software engineering methods & tools: goal modeling [k1, e2, p3], stakeholder modeling [e2, w3], agent modeling [d1], service modeling [g2], process modeling [d2, f2, l2], simulation [r3, l1]
- General purpose methods & tools: interviews [t1], statistics [p2], surveys [u1]
- Systems Engineering: life cycle assessment [f1, l1]
- Geo Sciences: global position system, internet map services [m1, w1]
- Earth Sciences: environmental information systems [p1, q3]
- Urban Planning: simulation [i1, d1]

TOPICS KNOWLEDGE AREAS	environmental management support climate stakeholders ecological **1**	cloud services emission components designing users **2**	communication servers smart grid industry integrated ULS **3**	software ICT consumption efficient carbon devices **4**	sustainable life cycle supply business assessment natural **5**	green processes virtualization land planet organization **6**	energy efficiency hardware optimization behavior manufacturing performance **7**	technology environment traffic global strategies production **8**	knowledge social architecture integration waste urban **9**	data future human change society quality **10**
Computing Foundations										
Engineering Foundations		1	1		1					1
Mathematical Foundations										
Software Configuration Management										
Software Construction		1								
Software Design		2	2		4	1	3	1	1	2
Software Engineering Economics		1							1	
Software Engineering Management	1		2	1	1				2	1
Software Engineering Models and Methods	3		1	2		1	3	1		3
Software Engineering Process		1	2	1			2	1	1	5
Software Engineering Professional Practice										
Software Maintenance										
Software Quality	1	1		1	4	2	1		2	2
Software Requirements	2		1	2		3			2	1
Software Testing										

TOPICS RESEARCH TYPES	1	2	3	4	5	6	7	8	9	10
Philosophical			1				1	1	1	1
Exploratory	2	3	1	3	3	1	3	1	2	4
Solution	4	3	6	2	5	3	5	1	2	5
Validation	1	1	1	2					2	3
Evaluation					2	2			1	
Opinion										
Experience						1			1	2

Figure 3: Top: Topic Clusters related to Knowledge Areas, Bottom: Topic Clusters related to Research Topics

- Energy Management: measuring devices [v2, k2, d3], traffic management systems [w1]

This plethora of used approaches only leads to the conclusion that there are many different roads being explored but there are no methods and models yet that can be considered as established for SE4S.

RQ4: Which models and methods are used in practice?.

In order to report on which means are used in practice (as opposed to being only proposed as a solution in a publication), when considering Fig. 3 it is clear that there are not many publications of the research facet *Evaluation* or *Experience*. *Evaluation* papers are [o2, p2, a3, r3, d4], and *Experience* papers are [b1, c1, e2, s3]. Due to this low number, it does not make sense to draw further conclusions on the state of practice. It also leaves the question of whether the topic is not really triggering a state of practice at all or whether it is simply not published much on yet.

RQ5: Which research methods have been considered in the contributions?.

In Fig. 5, we display the relation of knowledge areas [8] to research facets [7].

As represented in Fig. 5, there are many contributions of the type *Exploratory* and *Solution*, but on the other hand none of the type *Opinion* and very few in *Experience* and *Evaluation*. This indicates a young and still somewhat immature research area which needs to perform more evaluation and encourage practitioners to report on experiences.

RQ6: Which application domains have been considered?.

As not all publications are considering an explicit application domain, but more than 50% have a generic approach across application domains, we classified papers either according to an application domain or a focus domain to be able to differentiate them in categories. As opposed to the topic clusters discussed in RQ 1, these domains were not extracted automatically, but assigned manually by the researchers. Furthermore, a subsequent mapping between the automatically extracted research topic clusters and the application domains did not lead to significant correlation, thereby undermining the fact that they are worth distinguishing. We found ten such domains:

- Software Engineering & Lifecycle: Publications that do not refer to a specific application domain but presented generic approaches related to software engineering and the software lifecycle.
- Energy Efficiency: Publications that dedicate their work specifically to energy efficiency topics.
- Services, Mobile & Cloud: Publications that research topics in a service-oriented paradigm, often including mobile aspects and/or cloud computing, including research that monitors and improves traffic in cloud computing.

KNOWLEDGE AREAS \ RESEARCH TYPES	Philosophical	Exploratory	Solution	Validation	Evaluation	Opinion	Experience
Computing Foundations							
Engineering Foundations		4					
Mathematical Foundations							
Software Configuration Management							
Software Construction			1				
Software Design		6	8	2			
Software Engineering Economics		1					1
Software Engineering Management	2	3	2				1
Software Engineering Models and Methods	2	3	9				
Software Engineering Process	1	2	9	1			
Software Engineering Professional Practice							
Software Maintenance							
Software Quality		1	5	4	3		1
Software Requirements		3	2	3	2		1
Software Testing							

Figure 5: Correlation of Knowledge Areas to Research Facets.

Table 3: Number of Voted-in papers according to Application and Focus Domain

Application / Focus Domain	Publications
Software Engineering & Lifecycle	22
Energy Efficiency	5
Services, Mobile & Cloud	10
Business & Economics	5
Systems Engineering & ICT	12
ULS Green Computing	7
Mechanics & Manufacturing	3
Nature & Agriculture	5
Metropolitan Areas & Housing	9
Software Engineering Education	5

- Business & Economics: This focus domain includes publications on business processes and organizational issues as well as globalization.
- Systems Engineering & ICT: Many contributions go over the boundaries of software, but consider ICT and whole systems, leading to a broader application of the principles of sustainability.
- ULS Green Computing: (Ultra) Large-scale systems have become a focus in computing as optimization of software on that level can potentially have a big impact on the overall resource consumption of ICT.
- Mechanics & Manufacturing: Few contributions specifically address green (re-)manufacturing.
- Nature & Agriculture: This focus domain entails developing systems for supporting sustainability in agriculture as well as improving environmental modeling for monitoring nature and gaining insights on related data points and clusters (e.g., on climate change).
- Metropolitan Areas & Housing: A number of approaches targets urban management, including traffic, transportation, smart homes, and urban ecosystems.
- Software Engineering Education: Last but not least, five publications address how to incorporate the topic of sustainability into software engineering education.

The application domains and focus areas that have been considered in the publications are listed in Tab. 3. The publications are all referenced and clustered according to these domains in Tab. 4.
Figure 6 briefly summarizes the mapping of the manual classification of publications to Application Domains to the resultant topic cluster modeling classification of publications to the Topic Clusters. This figure shows the distribution of topics that occur in each of the application domains of the SE4S publications. Fig. 6 shows that the research topic clusters on the future of society, urban architecture and integration, energy efficiency, life cycle assessment, environmental management, smart grids, cloud services, carbon consumption, traffic strategies, and virtualization (as in Fig. 2) do not significantly correlate with the distribution of the application domains. However, alignments are perceivable for a small subset.

RQ7: Which research groups are most active in researching the topic and what is the distribution between academics and practitioners?.

The network graph was constructed based on the authors of the 83 voted-in publications. It was generated using Many Eyes[4], an experimental Visualization web service by IBM Research.
Apart from that there are a 197 unique authors, but as was shown in Fig. 4, most have been active in the last 3 years. We found 56 connected subgraphs (some of which were single author nodes), three of which are major research clusters, where authorship spans more than one or two papers. These are also fairly globally distributed, with even some intercontinental collaborations. These three interesting subgraphs are shown in Fig. 7 (a larger version can be found in [6]). The distribution of publications between academia and industry is currently unbalanced with roughly 80% of reported evidence coming from academia, the rest being distributed between industry and mixed collaborations. This distribution was derived from the affiliation that the authors provided for the publication.

Figure 7: Three largest author network subgraphs in detail; a larger version can be found in [6]

4. DISCUSSION & THREATS

This section provides a discussion of the results and of the threats to validity for this study.

Completeness of Results.

During the voting period, there were suggestions by reviewers for other papers they knew of, which they had expected to show up in the results but did not, were carefully checked by the principal researchers.

[4]`http://www-958.ibm.com/software/analytics/manyeyes/`

	environmental	cloud	communication	software	sustainable	green	energy efficiency	technology	knowledge	data
	management	services	servers	ICT	life cycle	processes	hardware	environment	social	future
	support	emission	smart grid	consumption	supply	virtualization	optimization	traffic	architecture	human
	climate	components	industry	efficient	business	land	behavior	global	integration	change
	stakeholders	designing	integrated	carbon	assessment	planet	manufacturing	strategies	waste	society
	ecological	users	ULS	devices	natural	organization	performance	production	urban	quality
TOPICS	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
APPLICATION DOMAINS										
Business and Economics	1		1						1	2
Energy Efficiency		1		1			3			
Mechanics and Manufacturing			1		2					
Metropolitan Areas and Housing	1			1	2		2	1		2
Nature and Agriculture	1		2						2	
Software Engineering and Life Cycle	3		1	4	3	2	2		3	4
Software Engineering Education		2	2		1					
Services, Mobile and Cloud		4			1		1	1		3
Systems Engineering and ICT	1			1	1	3	1		3	2
ULS Green Computing			2			2		1		2

Figure 6: Correlation of Application Domains to Topic classification

One reason for why some of the expected results had not shown up in the automatic search results was that they had not applied to the first part of the search string. The first part `(sustainab* OR ecolog* OR green)` required an explicit link of the research to sustainability concerns. This was not the case for many energy efficiency publications, therefore these may be underrepresented in the results of our study.
Another reason for missing expected results was that papers did not match the second part of the search query `(software engineering OR requirement* engineering OR requirement* specification OR software specification OR system specification)`. We encountered a few papers, for example, from the GREENS workshop at ICSE 2013, that we consider relevant to the research area, but did not show up in the results because they used other terms like 'software quality' to classify their research. We conclude that some software engineering researchers who work in the analyzed area of investigation are missing from the results because they used more specific terms and did not include the more general terms 'software engineering', or 'software specification', for example in energy efficiency and software quality.

Search Engine Correctness.

Each of the information sources (i.e. the indexing systems and digital libraries listed in 2) evaluated boolean search queries according to their own mechanism. Therefore, when an information source did specify query rules, the search string was adapted accordingly. An issue that was prevalent in some information sources was that there were different search results for semantically equivalent queries based on the order of operations. To this extent, we can not guarantee for the quality of the automatically executed queries in those information sources. However, as we used a wide range of search engines, we hope we have mitigated that effect as far as possible.

Manual Additions.

We have manually added a small set of proceedings of venues that are very relevant to the research area to the set of automatically retrieved papers due to the fact that the newest (2013) edition of these conferences and workshops was not yet indexed by the search engines. We did this in order to make the selection pool for relevant papers as up-to-date as possible. In our understanding, this does not introduce a strong bias for the research but rather merely offers a potential qualitative improvement of the results.

Data Synthesis.

The data synthesis was performed partially automatic, partially manually. For the automatic part, we relied on topic cluster modeling and generated graphics to aggregate information in a form that is more easily perceived by human cognition that pure numbers. These tools have been used widely throughout this and other research communities and we trust they are reliable and produce valid results. For the manual part, i.e. the classification according to knowledge areas, research facets, and focus domains, we performed the data synthesis to the best of our knowledge. However, human judgement is always subjective to a certain degree, so other researchers might have chosen slightly different terms for application domains or keywords for methods and frameworks. This threat was mitigated by internal and external reviews.

5. CONCLUSIONS

This paper presented a systematic mapping study to provide an overview of the current body of knowledge and research for software engineering for sustainability. This objective was detailed in seven research questions (RQ 1-7) on research topics, methods & tools, and application domains. The work was carried out by two principal researchers, three supporting researchers, an internal reviewer and two external reviewers over the course of 4 months. Please refer to the full report for additional information [6].
The topic of SE4S has received wide-spread attention in the software engineering community over the past few years. Due to the fact of being a relatively new area of research, there is rather little reported evidence of establishment in practice. At the same time, industry has recognized the topic and use the term *sustainability* all over, reminding of the *Green IT* hype, but now broadened to sustainability. As Green IT practices are by now further established in practice, hope remains that the same will come true for other sustainability practices. The low number of evaluation and experience papers in the reported evidence also suggest that the research area including its solutions are still somewhat immature. Furthermore, the fair distribution over a range of journals and venues indicates that the research community is still forming. However, the large number of topic clusters, focus areas and application domains indicates that research is being conducted in broad coverage of the area of SE4S. The following list sums up the major conclusions from the reported evidence.

RQ1 The research topic clusters that have been addressed include a variety of aspects ranging across the future of society, urban architecture and integration, energy efficiency, life cycle assessment, environmental management, smart grids, cloud services, carbon consumption, traffic strategies, and virtualization. The majority of publications are in the knowledge areas of *Software Design*, *Engineering Management*, *Models and Methods*, *Process*, *Quality*, and *Requirements*.

RQ2 Evolution of the research topics over time reveals a strong general development over the last four years, especially in the topic clusters of *future of society*, *life cycle assessment*, and *energy efficiency*.

RQ3 Sustainability support is performed by a variety of models and methods that include general purpose (interviews, statistics, surveys), software engineering (goals, stakeholders, services, processes), systems engineering (LCA), as well as methods from geo sciences, earth sciences, urban planning, and energy management.

RQ4 The usage of the approaches in practice is very limited in the reported evidence.

RQ5 The most prominent research type facets were *Exploratory* and *Solution*.

RQ6 The application domains that were predominantly considered are Software Engineering and Lifecycle, Systems Engineering and ICT, Energy Efficiency, Mobile Services and Cloud, Business and Economics, ULS Computing, Mechanics and Manufacturing, Nature and Agriculture, Metropolitan Areas and Housing, and Software Engineering Education.

RQ7 There are three rather active research groups but research is performed all over the world and distribution between academia and industry is currently unbalanced with roughly 80% of reported evidence from academia, the rest distributed between industry and mixed collaborations.

The aggregation of results and overviews in graphics and tables as well as the compact table of included publications may be considered as a compact overview of the field of Software Engineering for Sustainability.

Due to the facts that SE4S has significantly gained importance over the past few years and that it has been intensely researched by a world-wide community, we conclude that there is need for a future roadmap that identifies the major research gaps and outlines promising options of how to fill these gaps.

Acknowledgements. We would like to thank Daniel Méndez Férnandez and Marcela Genero for serving as external reviewers and for helpful feedback. This work is part of the DFG EnviroSiSE project (grant number PE2044/1-1).

6. REFERENCES

[1] L. Hilty, W. Lohmann, and E. Huang, "Sustainability and ICT — an overview of the field," in *Proceedings of the EnviroInfo 2011*, 2011.

[2] B. Brown, M. Hanson, D. Liverman, and R. Merideth, "Global sustainability: Toward definition," *EnvironmentalManagement*, vol. 11, no. 6, pp. pp. 713–719, 1987.

[3] L. Hilty et al., "The relevance of information and communication technologies for environmental sustainability," *Environm. Modelling & Software*, vol. 21, no. 11, pp. 1618 – 1629, 2006.

[4] B. Penzenstadler, V. Bauer, C. Calero, and X. Franch, "Sustainability in software engineering: A systematic literature review," in *International Conference on Evaluation and Assessment in Software Engineering (EASE)*, 2012.

[5] B. Kitchenham and S. Charters, "Guidelines for performing systematic literature reviews in software engineering," tech. rep., Software Engineering Group, Keele University, 2007.

[6] B. Penzenstadler, A. Raturi, D. Richardson, C. Calero, H. Femmer, and X. Franch, "Systematic mapping study on software engineering for sustainability (se4s) — protocol and results." `http://ics.uci.edu/~bpenzens/pdfs/SMSprot14.pdf`, 2014.

[7] R. Wieringa, N. Maiden, N. Mead, and C. Rolland, "Requirements engineering paper classification and evaluation criteria: a proposal and a discussion," *Requir. Eng.*, vol. 11, pp. 102–107, Dec. 2005.

[8] IEEE, "Software engineering body of knowledge (swebok)," 2013. `http://www.swebok.org`.

[9] T. L. Griffiths and M. Steyvers, "Finding scientific topics," *PNAS*, vol. 101, no. 1, pp. 5228–5235, 2004.

[10] D. M. Blei and J. D. Lafferty, *Text Mining: Classification, Clustering, and Applications*, ch. Topic Models, pp. 71–94. Chapman and Hall, 2009.

Table 4: Voted-in papers according to Application Domain

Ref	Year	Author	Title	Output Channel
			Application / Focus Domain: General Software Engineering & Lifecycle	
[a1]	1989	Cohill	The human factors design process in software development	3rd Intl. Conf. HCI
[z1]	2011	Johann et al.	Sustainable development, sustainable software, and sustainable software engineering: An integrated approach	IC Humanities, Science Engineering Research
[d2]	2011	Maharmeh, Saeed	Application of a composite process framework for managing green ICT applications development	Handbook of Research on Green ICT
[f2]	2011	Naumann et al.	The GREENSOFT Model: A reference model for green and sustainable software and its engineering	Sustainable Computing: Informatics and Systems
[l2]	2011	Shenoy, Eeratta	Green software development model: An approach towards sustainable software development	IEEE India Conference
[n2]	2012	Agarwal et al.	Sustainable approaches and good practices in green software engineering	J of Research and Reviews in Computer Science
[t2]	2012	Hindle	Green mining: Investigating power consumption across versions	ICSE
[w2]	2012	Johann et al.	How to measure energy-efficiency of software: Metrics and measurement results	W GREENS
[y2]	2012	Lami, Buglioni	Measuring Software Sustainability From a Process-Centric Perspective	W on Software Measurement
[a3]	2012	Noureddine et al.	A preliminary study of the impact of software engineering on GreenIT	W GREENS
[b3]	2012	Penzenstadler et al.	Sustainability in software engineering: A systematic literature review	IC EASE
[e3]	2012	Schubert et al.	Profiling Software for Energy Consumption	C GreenCom
[f3]	2013	Lago et al.	Exploring initial challenges for green software engineering	SIGSOFT SE Notes
[m3]	2013	Dick et al.	Green software engineering with agile methods	GREENS
[t3]	2013	Kern et al.	Green Software and Green Software Engineering – Definitions, Measurements, and Quality Aspects	ICT4S
[v3]	2013	Naumann	Classifying Green Software Engineering - The GREENSOFT Model.	J Software-Technik Trends
[w3]	2013	Penzenstadler et al.	Who is the advocate? Stakeholders for sustainability	W GREENS
[x3]	2013	Roher, Richardson	A proposed recommender system for eliciting software sustainability requirements	W USER
[y3]	2013	Kocak et al.	The Impact of Improving Software Functionality on Environmental Sustainability	ICT4S
[z3]	2013	Roher, Richardson	Sustainability requirement patterns	W RePa
[a4]	2013	Sventinovic	Strategic requirements engineering for complex sustainable systems	J Systems Engineering
[b4]	2013	Penzenstadler	Towards a definition of sustainability in and for software engineering	SAC
			Application / Focus Domain: Energy Efficiency	
[b2]	2011	Kutsuki	Developing and Providing Software that Helps to Reduce Environmental Burden	Fujitsu Journal
[p2]	2012	Capra et al.	Is software green? Application development environments and energy efficiency in open source applications	Information and Software Technology
[s2]	2012	Gotz et al.	Approximating quality contracts for energy auto-tuning software	W GREENS
[n3]	2013	Grosskop, Visser	Energy Efficiency Optimization of Application Software	B Green and Sustainable Computing
[r3]	2013	Grosskop, Visser	Identification of Application-Level Energy-Optimizations	ICT4S
			Application / Focus Domain: Services, Mobile & Cloud	
[m1]	2010	Ager et al.	Internet map services: new portal for global ecological monitoring, or geodata junkyard?	IC on Computing for Geospatial Research & Application
[o1]	2010	Bahsoon	A Framework for Dynamic Self-optimization of Power and Dependability Requirements in Green Cloud Architectures	Europ. Conf. on Software Architecture
[u1]	2011	Amsel et al.	Toward sustainable software engineering	IC on Software Engineering
[v1]	2011	Atkinson et al.	Modelling as a Service (MaaS): Minimizing the Environmental Impact of Computing Services	W GREENS
[c2]	2011	Lago, Jansen	Creating Environmental Awareness in Service Oriented Software Engineering	W Service-Or. Computing
[j2]	2011	Sasikala	Architectural strategies for green cloud computing: environments, infrastructure and resources	J on Cloud Applications and Computing
[c3]	2012	Razavian et al.	Modeling to support communication and engineering of service-oriented software	W Software Services and Systems Research
[g4]	2013	Atkinson, Schulze	Towards application-specific impact specifications and GreenSLAs	W GREENS
[k3]	2013	Chauhan, Saxena	A Green Software Development Life Cycle for Cloud Computing	J IT Professional
[l3]	2013	Corral et al.	A method for characterizing energy consumption in Android smartphones	GREENS
			Application Domain: Business & Economics	
[c1]	1994	Jones	Globalisation of software supply and demand	J Software Engineering
[g2]	2007	Ramakrishnan	Business process ontology and software service models for environmentally sustainable manufacturing enterprises	IC ITI
[k1]	2009	Cabot et al.	Integrating sustainability in decision-making processes: A modelling strategy	Intl Conf on Software Engineering
[y1]	2011	Harmon, Demirkan	The corporate sustainability dimensions of service-oriented information technology	SRII Global Conference
[e2]	2011	Mauhaux et al.	Discovering Sustainability Requirements: An Experience Report	WC Requirements Engineering: Foundations for Software Quality

Application / Focus Domain: Systems Engineering & ICT				
[b1]	1993	Atallah	Systematic methodology for developing advanced complex systems	Conf. CE and CALS
[h1]	2007	Rasmussen	From human-centred to human-context centred approach: looking back over 'the hills', what has been gained and lost?	AI & Society
[r1]	2010	Mitrea et al.	Sustainability ICT visions and their embedding in technology construction	Information Communication & Society
[t1]	2010	Sissa	Green Software	J UPGRADE
[x1]	2011	Curley	Towards sustainability: Harnessing computing and communications for a better future	Symp. on Computers and Communications
[h2]	2011	Philipson	A Framework for Green Computing	J of Green Computing
[i2]	2011	Ramaiya et al.	Architecture, design and development of a green ICT system	Handbook of Research on Green ICT
[m2]	2011	Taina	Good, bad, and beautiful software-in search of green software quality factors	J UPGRADE
[o3]	2013	Fors, Lennerfors	Translating Green IT: The Case of the Swedish Green IT Audit	ICT4S
[p3]	2013	Penzenstadler, Femmer	A generic model for sustainability with process- and product-specific instances	W GIBSE
[u3]	2013	Malmodin et al.	The Future Carbon Footprint of the ICT and E&M Sectors	ICT4S
[c4]	2013	*Track*	Software engineering for renewable energy systems	C IT-DREPS
Application / Focus Domain: ULS Green Computing				
[q2]	2012	Fakhar et al.	Software level green computing for large scale systems	J Cloud Computing
[r2]	2012	Ferreira et al.	Green Performance Indicators Aggregation through Composed Weighting System	ICT-GLOW
[u2]	2012	Chen, Kazman	Architecting ultra-large-scale green information systems	W GREENS
[v2]	2012	Sahin et al.	Initial explorations on design pattern energy usage	W GREENS
[z2]	2012	Liangli et al.	Virtualization Maturity Reference Model for Green Software	ICCECT
[d3]	2012	Sahin et al.	Towards power reduction through improved software design	C Energytech
[j3]	2013	Bokhoven, Bloem	Pilot Result Monitoring Energy Usage by Software Slides	ICT4S
Application / Focus Domain: Mechanics & Manufacturing				
[f1]	2002	Dong et al.	Research on the development of green product life cycle analysis tool	J China Mechanical Engineering
[j1]	2008	Zhou et al.	Green remanufacturing engineering in structural machinery based on reverse engineering	IC on Security Technology
[l1]	2009	Johansson et al.	Discrete event simulation to generate requirements specification for sustainable manufacturing systems design	W. on Performance Metrics for Intelligent Systems
Application / Focus Domain: Nature & Agriculture				
[e1]	1997	Ramalho-filho et al.	Use of geographic information systems in (planning) sustainable land management in Brazil: potentialities and user needs	IT C ICT Journal
[g1]	2004	Argent	An overview of model integration for environmental applications - components, frameworks and semantics	J Env. Modelling & Software
[p1]	2010	Bingshan et al.	Knowledge-based environmental information system for sustainable development of wetland area	IC on Software Engineering and Data Mining
[q1]	2010	Easterbrook et al.	Second International Workshop on Software Research and Climate Change	W Software Research & Climate Change
[q3]	2013	Grunfeld, Houghton	Using ICT for Climate Adaptation and Mitigation through Agro-Ecology in the Developing World	ICT4S
Application / Focus Domain: Metropolitan Areas & Housing				
[d1]	1997	Burmeister et al.	Application of multi-agent systems in traffic and transportation	Software Engineering. IEE Proc
[i1]	2007	Robinson et al.	SUNtool - a new modelling paradigm for simulating and optimising urban sustainability	J Solar Energy
[n1]	2010	Albertao et al.	Measuring the Sustainability Performance of Software Projects	IC on e-Business Engineering
[s1]	2010	Shishkov et al.	On the application of autonomic and context-aware computing to support home energy management	IC on Enterprise Information Systems
[w1]	2011	Bhalla, Chaudhary	Applying Service Oriented Architecture and Cloud Computing for a Greener Traffic Management	Handbook of Research on Green ICT
[a2]	2011	Kraines	Integrating distributed computational models as dynamic expressions of knowledge: the case for evaluating measures for urban ecosystem sustainability	W on Software Knowledge
[k2]	2011	Schrammel et al.	FORE-Watch - The Clock That Tells You When to Use: Persuading Users to Align Their Energy Consumption with Green Power Availability	IC Ambient Intelligence
[h3]	2013	Bloechle et al.	Developing a Strategy for the Implementation of ICT in Energy Efficient Neighbourhoods	ICT4S
[i3]	2013	Blumendorf	Building Sustainable Smart Homes	ICT4S
Application / Focus Domain: Software Engineering Education				
[g3]	2011	Penzenstadler, Fleischmann	Teach sustainability in software engineering?	CSEE&T
[o2]	2012	Ahmed, Shuaib	Incorporating Green IT concepts in undergraduate software requirements engineering course: An experience report	C Information Systems and Technologies
[x2]	2012	Penzenstadler et al.	Jumpstart sustainability in seminars: hands-on experiences in class	CSERC
[s3]	2013	Johnson et al.	Makahiki+WattDepot: An Open Source Software Stack for Next Generation Energy Research and Education	ICT4S
[d4]	2013	Penzenstadler et al.	University meets industry: Calling in real stakeholders	CSEE&T