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Introduction

Over the past 16 years the *International Conference on Evaluation & Assessment in Software Engineering* has provided a forum where empirical researchers can present their latest research, and where issues related to all forms of empirical and evaluation studies in software engineering can be discussed. The EASE tradition is one of providing a workshop-like atmosphere, in which papers can be presented with time for constructive discussion of their results and processes.

The 16th edition (EASE 2012) has been organized by the Alarcos Research Group and hosted by the Escuela Superior de Informática in the University of Castilla-La Mancha located at Ciudad Real (Spain).

A total of 72 full papers and 31 short papers were submitted from all over the world and of these 22 full papers (31%) and 14 short papers (45%) were accepted for presentation at the Conference and inclusion in the Conference Proceedings. These papers address topics such as systematic literature reviews and mapping studies, formal experiments, qualitative studies, estimation and empirical software engineering.

In addition to the research papers, there are two keynote speeches: the first by Professor Dieter Rombach, Chair for Software Engineering at the University of Kaiserslautern, and Executive Director of the Fraunhofer Institute for Experimental Software Engineering in Kaiserslautern, Germany, is on the topic of “Empirical Models: Towards a Science of Software Engineering”; the second, by Professor Helen Sharp, Professor of Software Engineering at The Open University, UK, is on the topic of “Ethnographic studies in Software Engineering”.

We would like to thank all of those who have contributed in numerous ways to making this conference a success: the authors for submitting their papers, the Program Committee members for their important work in reviewing and selecting the papers and in promoting the conference, the Executive Committee for agreeing to have the conference in Spain, the Organizing Committee together with all the people that helped in planning the conference, and the delegates. In addition, we would also like to thank all the sponsors to this event and the University of Castilla-La Mancha for hosting the conference.

We hope that you enjoy very much attending this conference and also your stay in Ciudad Real.

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Marcela Genero and Emilia Mendes (Program Co-Chairs)
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Sustainability in Software Engineering: A Systematic Literature Review

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***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[1] on the support of sustainability in software engineering. The full protocol is available online as technical report [4].

[1]One of the common motivators for SLRs named by Zhang and Babar in [3, Tab.I].

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 [3].

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?[2]
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.

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

Mahaux et al. [7] performed a preliminary search on the DBLP Computer Science Bibliography database[3]. 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 [1]. As SLR research questions we directly adopted those enumerated in Sec. I-D. The search process for this study is based on an automated search of the following digital libraries:

- IEEE Digital Library http://ieeexplore.ieee.org
- 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* OR environment* OR ecolog* OR green)
AND
(software 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

[3]http://dblp.mpi-inf.mpg.de/dblp-mirror/index.php

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): IEEEXplore, 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 assessment from the expert reviewers.

F. Data Analysis

The data is tabulated to show:

- The databases 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
NUMBER OF RESULTS PER DATABASE

Database	Date	Results
IEEE Xplore	27/12/11	319.601
ACM Digital Library	26/12/11	104.217
SpringerLink	29/12/11	500.004
ScienceDirect / Scopus	29/12/11	10.749
Web of Science	29/12/11	80.503

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

Table II
INCLUDED RESULTS FROM IEEE XPLORE, FULL REFERENCES IN APPENDIX [8]

Author and reference	Date	Pub.	Type	Topic	Domain	Benefit
Kung et al.	2011	CP	method	green decision-making framework	building construction	S App Dom
Middendorf et al.	2009	CP	method	envir. aspect in mechatronics design	mechatronics, robots	S App Dom
Ulieru	2010	CP	method	design for resilience of networked critical infrastructures	digital ecosystems	S App Dom
Albertao et al.	2010	CP	metrics	sustainability performance of software	eBusiness	S Concept
Zhou et al.	2008	CP	method	green remanufacturing engineering in structural machinery	security tech.	S App Dom

Table III
INCLUDED RESULTS FROM ACM, FULL REFERENCES IN APPENDIX [8]

Author and reference	Date	Pub.	Type	Topic	Domain	Benefit
Mouton et al.	2009	A	model	habitat suitability models for river management	ecological knowledge	S App Dom
Geist et al.	2009	A	challenges	computer science challenges at exascale	high performance computing	S SW Sol
O'Sullivan	2010	CP	method	data mining for biodiversity prediction in forests	forestry, data mining	S App Dom
Penzenstadler et al.	2011	CP	method	teach sustainability in software engineering	education	S in SE
Zhongjia et al.	2010	CP	prototype	design of self-propelled walking brush cutter	digital manufacturing	S HW Sol
Audisio et al.	2009	A	method	hazard management in two Alpine river basins	GIS tool	S App Dom
Miginsky et al.	2008	A	method	computer reconstruction of the biological networks	ecological networks	S SW Sol
Pennington et al.	2008	A	method	indirectly driven knowledge modeling in ecology	knowledge models	S Concept
Blevis et al.	2007	CP	reflection	design critique as research to link sustainability and interactive technologies	design research	S Concept
Adomavicius et al.	2007	A	model	technology roles & influence in an ecosystem model of technology evol.	technology ecosystem	S Concept
Pereira et al.	2009	A	method	knowledge discovery for coastal waters classification	environmental monitoring	S SW Sol
Henriksen et al.	2007	A	method	public participation modeling in management of groundwater contamination	groundwater management	s conc
Dick et al.	2011	CP	model	meta-design environments to motivate changes in energy consumption	energy sustainability	S SW Sol
Ticehurst et al.	2007	A	model	assessing the sustainability of coastal lakes	environmental management	S Concept
Shih et al.	2010	A	model	butterfly and wetland ecology for context-aware ubiquitous learning	mobile learning	S App Dom
Cushing et al.	2007	A	method	database design for ecologists	ecosystem info management	S SW Sol
Cushing et al.	2006	CP	overview	eco-informatics and natural resource management	eco-informatics	S Concept
Kang et al.	2008	A	method	GIS-based poultry litter management system for nutrient planning	decision support	S App Dom
Amsel et al.	2010	CP	tool	tool for estimating the energy consumption of software	green computing	S SW Sol
Choucri et al.	2011	WP	model	simulation modeling approach to evaluate renewable energy readiness	energy simulation	S App Dom
Vicat-Blanc et al.	2011	BC	model	optical networks and cloud as architecture for a sust. future internet	cloud	S App Dom
DesAutels et al.	2011	A	model	explore the market price of "sustainable" notebooks	life cycle analysis	S App Dom
Ramona	2009	CP	method	consolidating eco-economics through financial and fiscal instruments	eco-culture	S Concept
Mathevet et al.	2007	A	tool	role-playing game for collective awareness of wise reedbed use	environmental education	S App Dom
Salski	2007	CP	method	fuzzy approach to ecological data analysis	fuzzy systems	S Concept
Abidin et al.	2010	A	tool	tool to detect and predict urban growth pattern	neural network	S App Dom
Kase et al.	2008	CP	model	sustainable informal it learning in community-based nonprofits	education	S Concept
Prabhakar et al.	2010	A	model	transfer scheme for energy harvested WSN gateways	energy grids	S App Dom
Umstatter	2011	A	review	review of the evolution of virtual fences	electronics in agriculture	S App Dom
Vance	2007	CP	model	permanent coexistence for a linear response omnivory model	modeling	S App Dom
Pousman et al.	2008	CP	method	casual information visualization of printer data	sustainability design	S SW Sol
Fu et al.	2011	CP	framework	urban media framework of social innovation and service design	service design	S Concept

Table IV
INCLUDED RESULTS FROM SCIENCE DIRECT, FULL REFERENCES IN APPENDIX [8]

Author and reference	Date	Pub.	Type	Topic	Domain	Benefit
Abdulaziz et al.	2011	A	review	car parking requirements for sustainable transport development	transport	S App Dom
Alain et al.	2006	A	method	modeling living systems, their diversity and their complexity	agronomy systems	S App Dom
Alexandrov	2011	L	assessment	technical assessment and evaluation of environmental models	environmental modeling	S Concept
Ashraf et al.	2012	A	method	image data fusion for the remote sensing of freshwater environments	applied geography	S App Dom
Beusen et al.	2011	A	tool	dynamic simulation and visualization software for mathematical models	environmental modeling	S SW Sol
Bovea et al.	2012	A	tool review	taxonomy of ecodesign tools for integrating environmental requirements	clean production	S in SE
Brown et al.	2010	A	tool	software tool designed to verify ensemble forecasts of numeric variables	environmental modeling	S SW Sol
Cardona et al.	2011	A	model	software package developed for dynamic simulation of water quality in rivers	environmental modeling	S SW Sol
Cui et al.	2009	A	method	management-oriented valuation for ecol. water requirements for wetlands	nature conservation	S App Dom
Faith-Ell et al.	2006	A	case study	application of environmental requirements in Swedish road maintenance contracts	cleaner production	S App Dom
Fan et al.	2007	A	model	model for China's energy requirements and CO2 emissions analysis	energy	S App Dom
Fuller et al.	2006	A	tool	software package for optimizing connectivity in conservation planning	biodiversity protection	S SW Sol
Harmon et al.	2009	A	evaluation	exploratory evaluation of the market case for green energy	green energy	S App Dom
Hughes et al.	2010	A	framework	determination of environmental water requirements for rivers	environmental modeling	S App Dom
Justyna et al.	2010	A	review	green roof performance towards management of runoff water quantity and quality	ecological engineering	S App Dom
Kalivarapu et al.	2008	A	framework	software framework for modeling of contaminant transport in groundwater	environmental modeling	S SW Sol
Kit et al.	2012	A	tool	texture-based identification of urban slums in India using sensing data	applied geography	S SW Sol
Koormann et al.	2006	A	model	modeling down-the-drain chemicals in rivers	environmental modeling	S Concept
Kubba	2010	BC	strategy	green project requirements and strategies	architecture	S Concept
Liu et al.	2011	A	study	energy requirements and carbon dioxide emissions of tourism industry	energy	S App Dom
Mei et al.	2010	A	review	research progress of ecological water requirement in china	ecological informatics	S App Dom
Naumann et al.	2011	A	model	reference model for green and sustainable software and its engineering	software engineering	S in SE
Rizzo et al.	2006	A	evaluation	dynamic systems-based software packages for ecological systems	environmental modeling	S SW Sol
Smith et al.	2010	CP	method	green product design through product modularization using atomic theory	lean manufacturing	S Concept
Tong et al.	2011	A	method	generating the plan of mandatory green space in urban systems	urban development	S App Dom
Tseng et al.	2010	A	study	evaluating a firm's green supply chain management	cleaner production	S App Dom
Xu et al.	2010	A	review	review on ecological engineering based engineering management	management	S Concept
Yen et al.	2011	A	study	management's role in adopting green purchasing standards in industry	business research	S Concept
Zhang et al.	2011	A	study	costs and barriers of green property development in China	property development	S App Dom
Zhang et al.	2010	A	model	multi-source remote sensing data for estimating ecological water requirement	environmental modeling	S SW Sol

Table V
INCLUDED RESULTS FROM SPRINGER LINK, FULL REFERENCES IN APPENDIX [8]

Author and reference	Date	Pub.	Type	Topic	Domain	Benefit
Huang et al.	2009	CP	study	support green customers' decision process on electronic commerce	web engineering	S App Dom
Liao et al.	2009	CP	method	multimedia stream format and green design concept for e-learning	education	S Concept
Liu et al.	2008	A	method	wheat growth model multi-agent system	computing in agriculture	S SW Sol
Du	2010	A	method	neural network control for greenhouse management	computing in agriculture	S SW Sol
May et al.	2006	CP	method	composing biological workflows through web services	parallel processing	S SW Sol

Table VI
INCLUDED RESULTS FROM WEB OF SCIENCE, FULL REFERENCES IN APPENDIX [8]

Author and reference	Date	Pub.	Type	Topic	Domain	Benefit
Alvarez et al.	2011	A	method	decision making for treatment intensity in purifying plants	wastewater	S App Dom
Balana et al.	2011	A	review	cost-effectiveness analysis of agri-environmental measures	water pollution	S App Dom
Boose et al.	2007	CP	method	reliable datasets for environmental models with an analytic web	ecological data sets	S SW Sol
Bravi et al.	2011	A	assessment	life cycle assessment of a micromorph photovoltaic system	energy	S App Dom
Ellison et al.	2006	A	model	analytic webs support the synthesis of ecological data sets	ecological data sets	S SW Sol
Greene et al.	2010	A	method	decision analysis with exploration and evaluation phases	land management	S App Dom
Hall et al.	2011	A	method	requirements for 3D vegetation structure from space	environmental modeling	S SW Sol
I-Wah	2011	A	analysis	development and conditions of home-school cooperation	education	S Concept
Jia et al.	2011	A	case study	urban wetland planning in Beijing	ecological complexity	S App Dom
Jin et al.	2011	A	study	integrated calculation of ecological water demand for basin systems	water demand	S App Dom
Kaduk et al.	2011	A	method	redicting the time of green up in temperate and boreal biomes	climate change	S App Dom
Lundy et al.	2011	A	method	integrating sciences to sustain urban ecosystem services	geography	S Concept
McCabe	2006	A	overview	sustainable building design in Australia	eco-architecture	S App Dom
McIntosh et al.	2007	A	method	database design for ecologists including observation data	ecoinformatics	S SW Sol
Scheller et al.	2010	A	method	increasing the reliability of ecological models using SE techniques	software engineering	S in SE
Seppala et al.	2011	A	assessment	greenhouse gas emissions and material flows in Finland	clean production	S App Dom
Singh et al.	2011	A	method	resource conservation technology in rice-wheat cropping system	environment	S App Dom
Tao et al.	2008	CP	model	UML-based green alignment selection decision making model	intelligent computation	S in SE
Verweij et al.	2010	A	perspective	IT perspective on integrated environmental modeling	software engineering	S in SE
Wang et al.	2008	CP	method	systematic research on the cost control of the green industry	cost control	S Concept
Wang et al.	2009	CP	tool	web-based distributed certification system of green food	env. science	S SW Sol
Xu et al.	2007	A	evaluation	sustainability evaluation of a nature reserve project	environmental management	S App Dom
Zhang et al.	2011	A	assessment	combined biostabilization and landfill for solid waste	environmental management	S App Dom
Zhou et al.	2008	CP	method	green remanufacturing engineering in structural machinery	security technology	S App Dom

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

Name	Number of Included Results
IEEEXplore	5 out of 100
ACM Digital Library	32 out of 100
Springer Link	5 out of 100
Science Direct	30 out of 100
Web of Science	24 out of 100
Total	96 out of 500

Table VIII
INCLUDED RESULTS PER YEAR

Year	Number of Results
1991 - 2005	0
2006	9
2007	12
2008	11
2009	11
2010	21
2011	29
2012	3
Total	96

Table IX
INCLUDED RESULTS PER PUBLICATION TYPE

Publication Type	Number of Results
Journal articles	65
Book chapters	2
Conference papers	27
Workshop papers	1
Letters to the editor	1
Technical reports	0
Total	96

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. II-VI. The dimensions of the taxonomy are the degree of domain specifity, 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. II-VI. 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].

Figure 1. Weighted topic cloud, created with http://www.wordle.net/

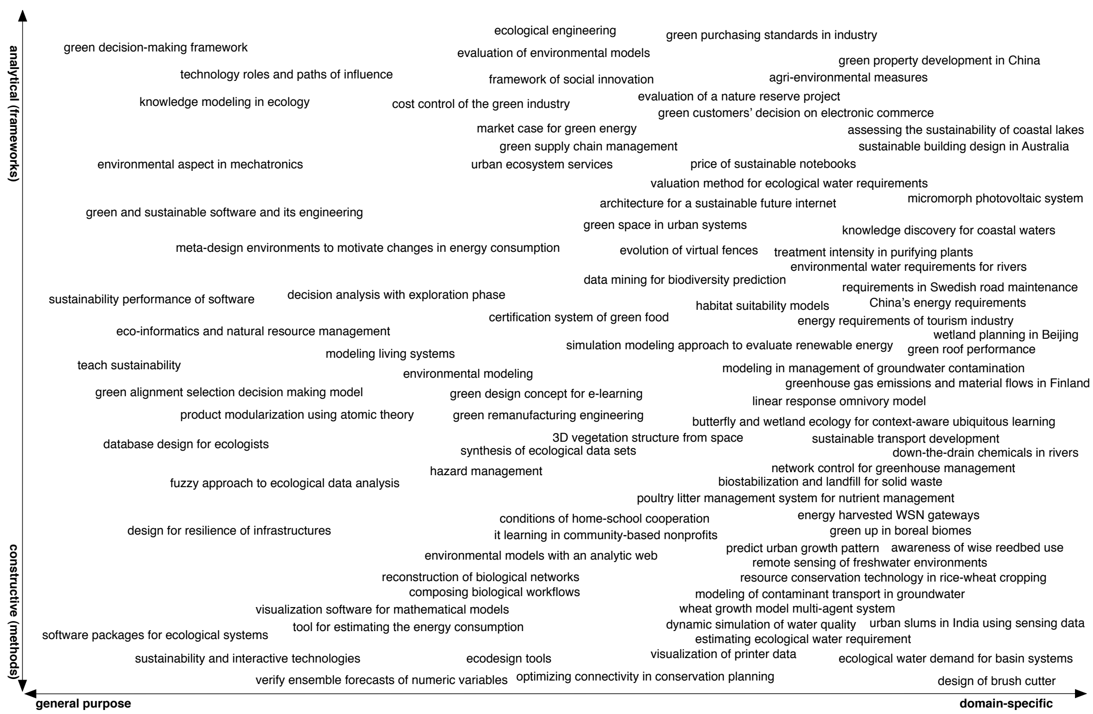

Figure 2. Taxonomy of research topics

- *High domain-specifity.*
  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]

Table X
INCLUDED RESULTS PER CONTENT TYPE

Class	Type of Content	Number of Results
Constructive	Method	36
	Model	18
	Metrics	1
	Framework	2
	Tool/Prototype	9
Empirical	Review	6
	Study	8
	Evaluation	3
	Assessment	4
Discussion	Overview	2
	Challenges	1
	Analysis	1
	Reflection	1
	Perspective	1
	Strategy	1

- Models, e.g., for software systems [14] or databases [16]
- Methods for specific application areas, e.g., security technology [13], green product design [17], or ecology knowledge [9]
- Metrics, e.g., for sustainability in eBusiness [18]

We chose just a few of the approaches for illustration and preferred the ones that are rather close to sustainability in software engineering. Furthermore, there are some empirical publications and rather few discussions.

RQ5: Which methods are in use?

There is a wide variety of methods in use for different purposes — we found traditional software engineering techniques as well as domain-specific techniques and methods from other disciplines.

Many approaches apply entity-relationship modeling, e.g. [9], as means to represent their data, knowledge, or information models. Neural networks are in use for dynamic environments and simulations, e.g. [19]. Methods adapted from other disciplines are, inter alia, cost calculations, e.g. [20], and life cycle analysis, e.g. [21].

RQ6: Are there case studies available?

We classified publications as case studies when they were explicitly named as such in the abstract and they were not, for example, only containing a small illustrative case study within a method proposal. The studies are listed in Tab. XI. Unfortunately, none of the studies contributes explicitly to an understanding of how to develop software for sustainable systems, but rather to analyses of specific application domains. Furthermore, publications that promote studies are often method proposals illustrated in a case study performed by the principal researcher.

RQ7: Which domains are already considered?

For an illustrated overview, please see the weighted domain cloud that visualizes the application domains in Fig. 3. 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

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

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 in Fig. 5.

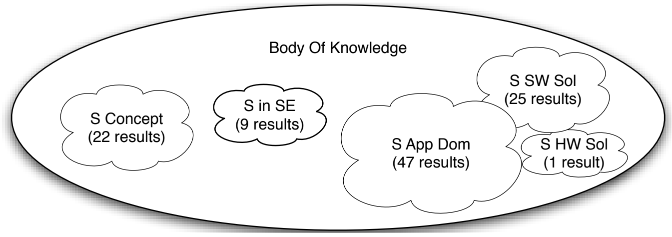

Figure 5. Areas of the Body of Knowledge for S in SE

Table XI
CASE STUDIES

Author and ref.	Domain	Context	Applied method
Huang et al. [10]	web engineering	support green customers' decision process on electronic commerce	questionnaire and experiment
Faith-Ell et al. [22]	cleaner production	application of environmental requirements in Swedish road maintenance	semi-structured interviews
Liu et al. [23]	energy	energy requirements and carbon dioxide emissions of tourism industry	index decomposition analysis
Tseng et al. [24]	cleaner production	evaluating a firm's green supply chain management	relational analysis, experiment
Yen et al. [25]	business research	management's role in adopting green purchasing standards in industry	questionnaires
Zhang et al. [26], [27]	property development	costs and barriers of green property development in China	cost analysis
Jia et al. [28]	ecology	urban wetland planning in Beijing	ecological complexity research
Jin et al. [29]	hydrology	ecological water demand for basin systems	integrated calculation

Figure 3. Weighted domain cloud, created with http://www.wordle.net/

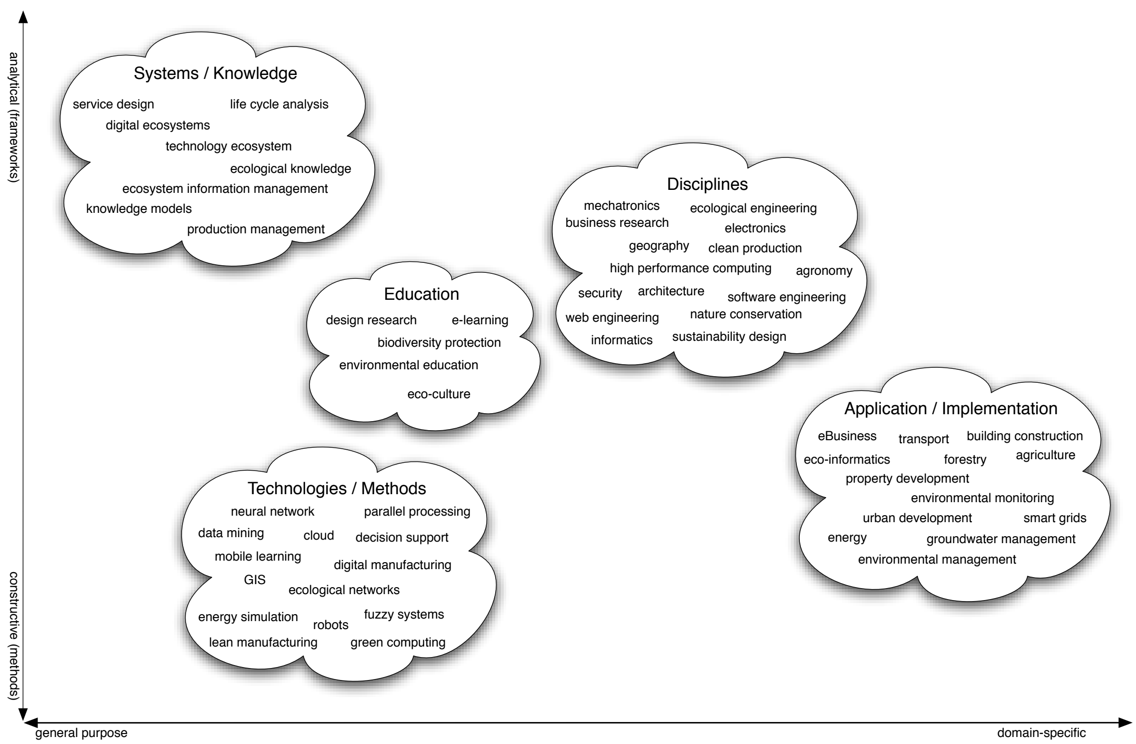

Figure 4. Taxonomy of application domains

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.[4]

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 "sustainab*" 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 IEEEXplore but was not included in the IEEEXplore 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.

[4]These 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.

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