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Sustainability in Software Engineering: A Systematic Literature Review for Building up a Knowledge Base

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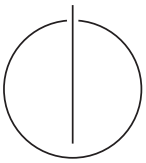

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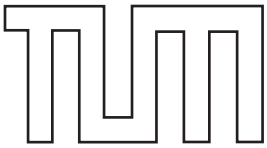

Sustainability in Software Engineering

A Systematic Literature Review for Building up a Knowledge Base.

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Abstract / Executive Summary

Background: Supporting sustainability in software engineering is becoming an active area of research and we want to contribute the first SLR in this field. Researchers who are motivated to contribute to that topic need to accumulate a body of knowledge as starting point through time-consuming literature research.

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 Systematic Literature Review (SLR) in five reliable and commonly-used databases according to the (quasi-standard) protocol by Kitchenham et al. [288]. 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. Most of the excluded publications were ruled out because of an unfitting usage of terms within the search query. We sketch a taxonomy of their topics and domains, and provide lists of used methods and proposed approaches.

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

Contents

1 Background

Systematic literature reviews are an accepted method for conducting secondary studies in software engineering [289, 114]. This report follows the quasi-standard protocol and guidelines by Kitchenham et al. [288, 286] to report on the current state of research and practice for supporting sustainability in software engineering.

1.1 Context

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 have to invest much time in finding a basic body of knowledge through literature research of many unrelated leads. Snowballing reveals some relations to further publications, but there are only a few isolated approaches that rather point to methodical and application-specific related work than to common underlying concepts and principles for sustainability.

This report is the protocol on our search for a solid basis of knowledge to investigate on supporting sustainability in software engineering. To clarify our research objective, we define our understanding of sustainability and what we mean by sustainability in software engineering.

1.1.1 Definition of Sustainability

The most cited definition of sustainable development [535] is to "meet the needs of the present without compromising the ability of future generations to satisfy their own needs." According to [535], sustainable development needs to satisfy the requirements of the three dimensions of society, economy, and environment. A fourth dimension, however, that is less present in the public discussion, but should be included according to [188] because it is the basis for the others, is human sustainability.

Human sustainability: Human sustainability refers to the maintenance of the private good of individual human capital. The health, education, skills, knowledge, leadership and access to services constitute human capital.

Social sustainability: Social sustainability means maintaining social capital and preserving the societal communities in their solidarity. Social capital is investments and services that create the basic framework for society: trust lowers transaction costs.

Economic sustainability: Economic capital should be maintained. The definition of income as the amount one can consume during a period and still be as well off at the end of the period can

define economic sustainability, as it devolves on consuming value-added (interest), rather than capital.

Environmental sustainability: Although environmental sustainability is needed by humans, it itself seeks to improve human welfare by protecting natural resources. These are water, land, air, minerals and ecosystem services; hence much is converted to manufactured or economic capital. Environment includes the sources of raw materials used for human needs, and ensuring that sink capacities recycling human wastes are not exceeded.

1.1.2 Sustainability Aspects in Software Engineering

ICT systems are amongst our most effective means to change how we interact with the world around us. These changes occur at a high rate and in shortening innovation cycles. This emphasis on short-term impacts draws the focus for many individuals and institutions away from long-term environmental well-being. Thus, ICT systems as they are currently deployed in society often serve as distractions from more important but less urgent long-term issues.

Consequently, for using the potential of ICT to change human interaction with the world towards more sustainable behavior, sustainability should be made a first class quality demand in software engineering. "Greening through IT" involves using what we have learned in information technology and related disciplines to make our life "greener" (in the sense of more environmentally sustainable) by providing adequate technological support for the actions of our daily life [524]. In contrast, in order to delimit our research and make the wording unambiguous, Green IT or "greening of IT" is making hardware and software of ICT systems more energy-efficient and using renewable energy sources; we do not focus on this in the SLR.

The challenge is to analyze how to reduce man's impact on the environment by finding new approaches in ICT that explicitly take sustainability into account. We call these systems "ICT for environmental sustainability" and abbreviate them with ICT4ES. Our aim for future research is to support the development of ICT4ES with an adequate software engineering approach that integrates the knowledge of environmental informatics.

Many of these solutions signify a change towards higher efficiency, but higher efficiency is not necessarily the key for making the world more environmentally sustainable. A big part of turning our life on this planet into a more sustainable one is about optimizing resource usage and saving energy. At the same time, there is the paradox that eventually optimizing their usage does not save resources — instead, for many challenges it will be more sustainable to choose a different solution instead of optimizing the existing one [523]; for example, setting up a videoconference instead of travelling to weekly business meetings, or car sharing instead of making fuel usage more efficient — little development effort with high fuel savings compared to very high effort for little fuel savings.

Sustainability aspects can be brought to bear both during the development and use of software systems. We distinguish four aspects of sustainability (orthogonal to the dimensions introduced in Sec. 1.1.1). The development process viewpoint includes:

- *Development process aspect*: Sustainability in the initial software development process (with responsible use of ecological, human, and financial resources).
- *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).
- *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).

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.

1.1.3 A Body of Knowledge for Sustainability in SE

Our research aim for the next years is to support the development of ICT4ES with an adequate software engineering approach that integrates the knowledge of environmental informatics. 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 primary study in form of a systematic literature review [583].

1.2 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:

1. How much activity was there in the last 20 years (1991-2011)?[1]
2. What research topics are being addressed?
3. What are the limitations of current research?

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

4. How is sustainability support performed?
5. Which methods are in use?
6. Are there case studies available?
7. Which domains are already considered?

1.3 Related Work

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

Mahaux et al. [345] performed a preliminary search on the DBLP Computer Science Bibliography database[2]. 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.

As we see great potential for learning from other domains, it was important for this systematic literature review not to restrict the search to software-related venues, which is the main reason why we received more results. In contrast to [345], we are interested in publications from all scientifically sound venues and journals as long as the topic fits our search criteria.

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

2 Search Design and Process

The search design and procedure follow the guidelines by Barbara Kitchenham et al. [288]. The protocol follows the structure proposed by Kitchenham et al. (2008) in "Protocol for Extending an existing Tertiary study of Systematic Literature Reviews in Software Engineering" [287] of which the results were published in [289]. The search process for this study will be based on an automated search of the following digital libraries covering the time period of 1991 - 2011:

- 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

2.1 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)

In case the data base does not support such a complex search string, we use the following equivalent list of search strings:

- (sustainab*) AND (software engineering OR requirement OR software systems)
- (environment*) AND (software engineering OR requirement OR software systems)
- (ecolog*) AND (software engineering OR requirement OR software systems)
- (green) AND (software engineering OR requirement OR software systems)

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

2.2 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

2.3 Exclusion Criteria

- Publication before 1991
- Purely hardware (GreenIT)
- Purely application in environmental domains (e.g., agricultural support systems with no explicit relation to sustainability)
- "Environment" used in the sense of system environment, not nature.
- "Ecosystem" used as population of interacting systems, for example, agents.
- Pure software engineering papers that are not related to sustainability.

2.3.1 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 introduced an additional result classification: domain-specific papers that are interesting to learn from but are not focussed on software engineering.
5. The principal researcher extracts statistics and analysis the included results in further detail.

2.4 Roles and Responsibilities

- Birgit Penzenstadler, Technische Universität München (TUM): principal researcher, search on IEEEXplore, search result classification, detailed analysis
- Zolboo Ochirsukh, TUM: student research assistant, search on ACM digital library
- Elena Mircheva, TUM: student research assistant, search on Web of Science
- Duc Tien Vu, TUM: student research assistant, search on ScienceDirect
- Tuan Duc Nguyen, TUM: student research assistant, search on SpringerLink
- Veronika Bauer, TUM: expert reviewer, assessment of search result classification, review of detailed analysis
- Coral Calero, Universidad de Castilla-La Mancha (UCLM): expert reviewer, assessment of search result classification, review of detailed analysis
- Xavier Franch, Universitat Polytecnica de Catalunya (UPC): expert reviewer, assessment of search result classification, review of detailed analysis

2.5 Quality Assessment

What quality criteria do the articles have to fulfill in order to be included in the results? There are no assessed quality criteria across all types of publications in terms of a database like, for example, DARE[1] for systematic reviews which was used by Kitchenham et al. [286], that we can rely on.

As we are interested in a broader spectrum of publications, our quality criteria are more general.

- Commonly accepted venue or journal.
- Scientifically sound approach.

2.6 Data Collection

The data collection is reported on per database and per search string.

[1] http://www.crd.york.ac.uk/CRDWeb/HomePage.asp

Table 2.1: Data Collection Form

Title	
Authors	
Publication	
Language	
Abstract	
Keywords	
Date	
Database	

2.7 Data Analysis

The data is tabulated to show:

- The database and total number of search query results. (RQ1)
- Listed by database for included publications:
  - Author and reference
  - Date (RQ1)
  - Publication type (RQ1)
  - Type of content (RQ6)
  - Topic of content (RQ2, RQ4, RQ5)
  - Domain (RQ7)
  - Benefit for our body of knowledge (RQ4)
- Listed by database for excluded publications: Author and reference , Topic, and Domain (with these notes revealing why the publication was excluded).
- 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.

3 Results

The overall number of results for each data base is listed in Tab. 3.1. Depending on whether it was possible to use the complete search string or not, the numbers are given as total or for the sub search strings.

The complete search string is:
(sustainab* OR environment* OR ecolog* OR green)
AND
(software engineering OR requirement OR software system)

Table 3.1: Number of Results per Database

Database	Date	Results	Search string
IEEE Xplore	27/12/11	319.601	complete search string
ACM Digital Library	26/12/11	927	(sustain*) AND ...
		88.579	(environment*) AND ...
		502	(ecolog*) AND ...
		14.209	(green) AND ...
SpringerLink	29/12/11	500.004**	complete search string
ScienceDirect / Scopus	29/12/11	10.749	complete search string
Web of Science	29/12/11	80.503	complete search string

**(with 141.502 from Informatics, 109.829 from Software Engineering)

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 when the full search string could be applied, and the first 25 of each result when the sub strings had to be applied (ACM). In total, we reviewed 500 publications.

The following abbreviations are used to categorize the findings in the tables during the next sections (Tab. 3.2-3.10):

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 domain 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*)

3.1 IEEE Xplore

Both the results that were included (Tab. 3.2) as well as the results that were excluded (Tab. 3.3) are ranked in the order as found in the search query results. The three top-most results that were included were also the top results of the search query results.

Table 3.2: Included Results from IEEE Xplore

Author and reference	Date	Pub.	Type	Topic	Domain	Benefit
Kung et al. [302]	2011	CP	method	green decision-making framework	building construction	s app dom
Middendorf et al. [368]	2009	CP	method	envir. aspect in mechatronics design	mechatronics, robots	s app dom
Ulieru [532]	2010	CP	method	design for resilience of networked critical infrastructures	digital ecosystems	s app dom
Albertao et al. [12]	2010	CP	metrics	sustainability performance of software	eBusiness	s concept
Zhou et al. [592]	2008	CP	method	green remanufacturing engineering in structural machinery	security tech.	s app dom

Of these included results, the expert reviewers considered three papers as rather domain-specific papers without explicit focus on software engineering. The domain-specific papers are [302], [368], and [532].

Table 3.3: Excluded Results from IEEE Xplore

Author and reference	Topic	Domain
Jansma [250, 251, 252]	software training program in an engineering and scientific environment	aerospace
Aoyama [27]	aspect-oriented SE	software processes
Jackson [246]	specialising in software specifications	SE
Chittister et al. [93]	systems integration via software risk management	software processes
Farkas et al. [155]	embedded software design	SE
Skramstad [497]	reverse engineering tools	reverse eng.
du Bousquet [140]	software validation	telecommunication
Tahvildari et al. [512]	requirements driven software evolution	program comprehension
Gomaa et al. [184]	configuring distributed applications from reusable software architectures	SE
Verrall et al. [542]	inter-operation problems of heterogeneous tools	SE
Mohamed [377]	value estimation for software product management	engineering management
Estublier et al. [149]	composites in software engineering environments	SE
DeBellis [126]	user-centric software engineering	SE
Tilley et al. [521]	migrating software testing to the cloud	software maintenance
Stuebing [507]	software engineering environment for weapon system software	SE
Whitehead [560]	collaboration in software engineering	SE
Coleman [100]	interactive software requirements	SE
Purvis [435]	capture of requirements and design rationale	education
Sharon et al. [484]	software engineering environment	SE
Maqbool [352, 353]	software clustering and reverse engineering	software maintenance
Cowan et al. [108]	distributed software engineering environments	SE
Ying et al. [575]	integrating AI techniques into CASE environment	artificial intelligence
Naveda et al. [396]	professional certification of software engineers	education
Liu et al. [330, 329, 331]	service-oriented requirements and software assets	SE
Green [192]	surveillance and tracking system software development	SE
Biuk-Aghai [47]	environments for distributed teams	software development
Smojver et al. [500]	process model for a complex software system integration	telecommunications
Hamilton-Jones et al. [209]	software technology for strike fighter avionics	avionics
Rose et al. [456]	organizing software repositories modeling requirements	SE
Gimenes et al. [181]	process-centered software engineering environments	air traffic control
Breu [59]	change-driven software engineering	software development
Li et al. [320]	linkage between source code and evolvable domain knowledge	software evolution
Schaschinger [470]	object-oriented analysis in knowledge engineering	SE
Dahanayake et al. [118]	database support for software engineering environments	SE
Cheng et al. [87]	interflow system requirement analysis	health informatics
Gao et al. [171]	internet-based, global software engineering environment	SE
Zhang et al. [581]	evaluation of process modeling methods	software processes
Arndt [28]	software evolution	multimedia applications
Ellis et al. [145]	a knowledge-based course engineering system	education
Miguel et al. [353]	knowledge and data base for software systems	tools for AI
Mujtaba [383]	software product customization process with value stream maps	SE
Damian [119]	requirements engineering in distributed software projects	requirements
Minot et al. [372]	object management system	programming tools
Rahimian et al. [437]	agile methodology for mobile software development	SE
Campbell et al. [71]	asynchronous requirements engineering	distributed development
Balikuddembe [34]	software project profitability	software projects
van Lamsweerde et al. [539]	obstacles in goal-oriented requirements engineering	SE
Takeda et al. [513]	meta language for software engineering	knowledge engineering
Andersson et al. [22]	deployment in software “environment”	pervasive computing
Colonese et al. [103]	component-based interoperability framework	real-time systems
to be continued …		

Author and reference	Topic	Domain
Weber [558]	integrated hardware and software reuse environment	systems engineering
Snyder [501]	synthetic vision systems	avionics
Islam et al. [245]	software development risk management model	SE
Chiken et al. [89]	group-based software engineering education	SE education
Llamosa et al. [333]	process management model for higher education in software quality	software quality
Hallsteinsen et al. [207, 208]	dynamic software product lines	SE
Moon [379]	developing domain requirements as a core asset	product lines
Antonini et al. [26]	legacy in software "environments"	sw maintenance
Sidoran [490, 491]	requirements engineering workstation and rapid systems prototyping	rapid prototyping
Luckey et al. [335]	improving software quality utilizing an integrated CASE environment	software quality
Norton et al. [401]	simulation of integrated electric propulsion systems	electric ship technologies
Cai et al. [69]	agent-based distributed software development	distributed computing
Dagli et al. [117]	heuristics for systems engineering management	systems engineering
Wette [559]	computer-aided engineering system	tools
Kutsche et al. [304]	meta data support for evolutionary software systems	SE
van der Burg et al. [538]	automating system tests	software reliability
Heimdahl et al. [223]	prototyping of control systems	avionics
Konyk [293]	personal positioning system approach	education
Hines [229]	conceptual object-oriented software engineering environment	SE
Burns [64]	requirements engineering environment	software requirements
Wang et al. [554]	network architecture and software engineering	broadband comm.
Hainaut [205]	data reverse engineering	reverse engineering
Finnigan et al. [160]	legacy software systems	SE
Landauer et al. [309]	collaborative system engineering and integration environments	enterprise software
Jarke et al. [255]	project on theories underlying requirements engineering	SE
IEE Colloquium [1]	software "environment" concerns	SE
Diaz-Gonzalez et al. [133]	prototyping conceptual models of real-time systems	systems eng.
Liu et al. [327]	multi-agent based enterprise software engineering	electric power decision support
Kaindl et al. [269]	iterative requirements engineering and architecting	SE
Bhatti et al. [44]	policy engineering	access management
Cugola et al. [109]	distributed process support system	process engineering
Yague et al. [569]	knowledge stored in systems models to derve validation tools	cognitive systems
Adsit [7]	engineering "environment"	engineering
Bastidas et al. [37]	distributed supervisory system design	industrial electronics
Mishra [373]	leadership in a systems acquisition life cycle	engineering management
Collens [102]	lessons learned from complex system development	systems eng.
Kaiser [270]	transaction model for software engineering	SE

All of the excluded papers were excluded because they used the term "environment" in a different sense, i.e. either as educational environment describing a classroom setting, or (in most cases) in the sense of an artificial system environment instead of the natural environment in our ecosystem.

3.2 ACM Digital Library

As the ACM search interface does not allow for such a complex search string, we had to split into the following four simpler strings. To take an equivalent look at the results, we read the 25 first results of each of the four queries.

- (sustainab*) AND (software engineering OR requirement OR software systems)
- (environment*) AND (software engineering OR requirement OR software systems)
- (ecolog*) AND (software engineering OR requirement OR software systems)
- (green) AND (software engineering OR requirement OR software systems)

Included results are in Tab. 3.4, excluded results in Tab. 3.5.

Table 3.4: Included Results from ACM Digital Library

Author and reference	Date	Pub.	Type	Topic	Domain	Benefit
Mouton et al. [381]	2009	A	model	habitat suitability models for river management	ecological knowledge	s app dom
Geist et al. [176]	2009	A	challenges	computer science challenges at exascale	high performance computing	s SW sol
O'Sullivan [405]	2010	CP	method	data mining for biodiversity prediction in forests	forestry, data mining	s app dom
Penzenstadler et al. [418]	2011	CP	method	teach sustainability in software engineering	education	S in SE
Zhongjia et al. [590]	2010	CP	prototype	design of self-propelled walking brush cutter	digital manufacturing	s HW sol
Audisio et al. [30]	2009	A	method	hazard management in two Alpine river basins	GIS tool	s app dom
Miginsky et al. [369]	2008	A	method	computer reconstruction of the biological networks	ecological networks	s SW sol
Pennington et al. [417]	2008	A	method	indirectly driven knowledge modeling in ecology	knowledge models	s concept
Blevis et al. [48]	2007	CP	reflection	design critique as research to link sustainability and interactive technologies	design research	s concept
Adomavicius et al. [6]	2007	A	model	technology roles & influence in an ecosystem model of technology evol.	technology ecosystem	s concept
Pereira et al. [420]	2009	A	method	knowledge discovery for coastal waters classification	environmental monitoring	s SW sol
Henriksen et al. [226]	2007	A	method	public participation modeling in management of groundwater contamination	groundwater management	s conc
Dick et al. [134]	2011	CP	model	meta-design environments to motivate changes in energy consumption	energy sustainability	s SW sol
Ticehurst et al. [520]	2007	A	model	assessing the sustainability of coastal lakes	environmental management	s concept
Shih et al. [487]	2010	A	model	butterfly and wetland ecology for context-aware ubiquitous learning	mobile learning	s app dom
Cushing et al. [112]	2007	A	method	database design for ecologists	ecosystem info management	s SW sol
Cushing et al. [113]	2006	CP	overview	eco-informatics and natural resource management	eco-informatics	s concept
Kang et al. [273]	2008	A	method	GIS-based poultry litter management system for nutrient planning	decision support	s app dom
Amsel et al. [21]	2010	CP	tool	tool for estimating the energy consumption of software	green computing	s SW sol
Choucri et al. [95]	2011	WP	model	simulation modeling approach to evaluate renewable energy readiness	energy simulation	s app dom
Vicat-Blanc et al. [544]	2011	BC	model	optical networks and cloud as architecture for a sust. future internet	cloud	s app dom
DesAutels et al. [130]	2011	A	model	explore the market price of "sustainable" notebooks	life cycle analysis	s app dom
Ramona [439]	2009	CP	method	consolidating eco-economics through financial and fiscal instruments	eco-culture	s concept
Mathevet et al. [357]	2007	A	tool	role-playing game for collective awareness of wise reedbed use	environmental education	s app dom
Salski [465]	2007	CP	method	fuzzy approach to ecological data analysis	fuzzy systems	s concept
Abidin et al. [5]	2010	A	tool	tool to detect and predict urban growth pattern	neural network	s app dom
Kase et al. [276]	2008	CP	model	sustainable informal it learning in community-based nonprofits	education	s concept
Prabhakar et al. [431]	2010	A	model	transfer scheme for energy harvested WSN gateways	energy grids	s app dom
Umstatter [534]	2011	A	review	review of the evolution of virtual fences	electronics in agriculture	s app dom
Vance [540]	2007	CP	model	permanent coexistence for a linear response omnivory model	modeling	s app dom
Pousman et al. [430]	2008	CP	method	casual information visualization of printer data	sustainability design	s SW sol
Fu et al. [165]	2011	CP	framework	urban media framework of social innovation and service design	service design	s concept

Table 3.5: Excluded Results from ACM Digital Library

Author and reference	Topic	Domain
Lombardo et al. [334]	energy savings and QoS in internet access routers	green IT
Jeong et al. [258]	collaborative argumentation in asynchronous discussions	education
Allender [14]	approaches on circuit lower bounds	mathematics
Sharifloo [483]	agility in ontologies	SE
Schankin [469]	contextual cueing	cognitive systems
Sharf [482]	space-time surface reconstruction	data engineering
Fuxman [169]	wisdom of the crowd keyword generation	keyword generation
Bianzino [45]	framework analysis for energy-efficiency in networks	green IT
Siddiqui [489]	supply chain simulator	education
Mahajan [344]	vehicular ad hoc networks in urban settings	networks
Al Bouna [55]	access control model with multimedia signatures	access control
Gunia [200]	metadata for long-term data preservation	data curation
Broxvall [61]	middleware for ecologies of robotic devices	robotics
Song [502]	adaptive awareness coverage control for multi-agent networks	adaptive control
Bertelle [42]	organization detection for dynamic load balancing in simulations	simulations
to be continued …		

Author and reference	Topic	Domain
Gutierrez [201]	modeling light scattering for virtual cultural heritage	high-fidelity graphics
Mandrioli [350]	student contest on software engineering	SE
Slawioski [498]	control scheme for teleoperation of mobile robots	robotics
Fattal [156]	blue-noise point sampling using kernel density model	stochastic sampling
Naiksatam [391]	enabling guaranteed bandwidth through deterministic and efficient provisioning	supercomputing
Chen [82]	adaptive e-news to improve undergraduate programming courses	education
Gaber [170]	action selection algorithms for autonomous system in pervasive environment	context awareness
Candea [72]	performance and high query concurrency for data analytics	data warehouse
Thies [519]	modeling web-oriented architectures	conceptual modeling
Al-Khalidi [9]	range search in mobile navigation	approximation
Green-Fishback [193]	runtime-configurable data product ensembles	scientific mashup system
Hirsig [230]	synergy in simulation modeling by architects and engineers	collaboration
Cui [111]	construction of biology teaching methodology program	education
Li [319]	regulate frequency of interconnected power system	automatic generation control
Puente [432]	doctor rostering problem in a hospital emergency department	genetic algorithms
Balicki [33]	decision making in distributed systems by quantum evolutionary algorithms	algorithms
Hadi [203]	management of target-tracking sensor networks	sensor networks
Wang [552]	blog-based dynamic learning map	education
Chin [91]	assessing new product development project risk by Bayesian network	probability
Laforcade [306]	specification of visual instructional design languages	visual models
Lezcano [318]	interoperability of electronic healthcare information systems	ontologies
Waszniowski [557]	formal verification of multitasking applications	model-checking
Wohlisch [563]	predictable large-scale data delivery in prefix-based virtualized content networks	networks
Cherubini [88]	large-scale diagram to help developers stay oriented in their code	visualizations
Kontitsis [292]	tracking system for small unmanned aerial systems	tracking
Roberts [451]	work-efficient GPU algorithm for level set segmentation	algorithms
Mandal [349]	integrating existing scientific workflow systems	programming models
Carlsson [76]	effective utilization of computer systems	green IT
Tripp [526]	effective taint analysis of web applications	program analysis
Trueba [527]	task-driven species in evolutionary robotic teams	robotics
Jermann [259]	interaction regulation in collaborative problem solving	HCI
Petrov [424]	adaptive control of a two-vehicle autonomous convoy	autonomous vehicles
Peachavanish [414]	ontological engineering approach for integrating CAD and GIS	infrastructure management
Talj [514]	control of the air supply system of a PEM fuel cell model	fuel cells
Fuentes [166]	requirements elicitation and analysis of multiagent systems using activity theory	AOSE
Manvi [351]	agent-based approach to intrastream synchronization for multimedia	mobile agents
AlAhmadi [8]	data gathering scheme for large scale wireless sensor networks	infrastructure
Windmann [562]	lateral versus medial orbitofrontal cortex activation to choice outcome processing	decision making
Lee [315]	measuring effectiveness of pedestrian facilities using a pedestrian simulation model	pedestrian simulation
Musunoori [385]	application service placement in stochastic grid environments	service configuration
Resmerita [445]	modeling and simulation of TDL applications	formal methods
Schmitz [473]	communication system for reconfigurable mechatronic modules	communication
Kim [283]	modeling and access control for data sharing in collaborative design	collaboration
Kulesza [301]	systematic testing approach for intelligent assistants	end-user programming
Kujala [300]	limits of capacity-based measures for revealing unsafe visual sampling models	control theory
Vytlacilova [546]	properties of fiber reinforced concrete using recycled aggregates	fibre materials
Gawaly [174]	impact of section 404 on information security	IT security
Wang [551]	image matting with transductive inference	image processing
Tung [530]	design framework for service innovation	services
Chen [85]	fingerprint verification on medical image reporting system	digital signature
Wang [555]	communication services using model-driven development	MDD
Ma [340]	implementation of imperfect models in fuzzy object-oriented databases	fuzzy logics
Zhu [593]	agents interactions in knowledge intensive multi-agent systems for networked information services	agents

The excluded papers were omitted when the term “environment” or “ecosystem” signified artificial surroundings in robotics, mobile agents, access control, data management, or in social contexts for education.

3.3 Springer Link

Included results are in Tab. 3.6, excluded results in Tab. 3.7.

Table 3.6: Included Results from Springer

Author and reference	Date	Pub.	Type	Topic	Domain	Benefit
Huang et al. [239]	2009	CP	study	support green customers' decision process on electronic commerce	web engineering	s app dom
Liao et al. [322]	2009	CP	method	multimedia stream format and green design concept for e-learning	education	s concept
Liu et al. [328]	2008	A	method	wheat growth model multi-agent system	computing in agriculture	s SW sol
Du [138]	2010	A	method	neural network control for greenhouse management	computing in agriculture	s SW sol
May et al. [358]	2006	CP	method	composing biological workflows through web services	parallel processing	s SW sol

Table 3.7: Excluded Results from Springer Link

Author and reference	Topic	Domain
Buckl et al. [62]	building blocks for enterprise architecture management solutions	enterprise architecture
Pagano et al. [407]	certified development tools implementation in objective caml	declarative languages
Angiulli et al. [25]	data condensation for nearest neighbor classification	parallel processing
Lee et al. [313]	usage-centered interface design for quality improvement	interface design
Park et al. [409]	incorporation of user preferences into mobile web service conversations	web services
Niedermayer et al. [398]	home networks and cloud computing for a future internet of things	internet
Degiovanni et al. [127]	automated test generation from formal tabular requirements	testing
Lee et al. [314]	data integration for collaborative assembly design information sharing	artificial intelligence
Chintan et al. [20]	software coupling in open source projects	open source software
Kadenbach et al. [267]	software support for online communities for teaching	online communities
Jiang et al. [261]	testing interface customized components	autonomic computing
Wijaya et al. [561]	web concepts to deliver business value	knowledge society
Mahbub et al. [346]	replacement policies for service-based systems	service-oriented computing
Helal et al. [224]	space sensing of networked robots	robotics
Nam et al. [394]	learning-based symbolic assume-guarantee reasoning	automated verification
Chang et al. [80]	host security with external environment sensors	security
David et al. [123]	sensor placement for monitoring indoor scenes	sensors
Gorodetsky et al. [189]	agent-based software development environment	AOSD
Marinucci [354]	talk about the power of data	data management
Chini et al. [92]	architecture for URI management with rich semantics	internet
Terho [518]	mobile web services and software quality	mobile software
Du et al. [139]	clustering of speech recognition models	neural networks
Kausar et al. [278]	analysis of encryption schemes for pervasive computing	information security
Al-Safi et al. [10]	ontology-based reconfiguration agent for mechatronic systems	multi-agents
Zignale et al. [596]	design of services in collaborative business environments	services
Mates et al. [356]	social analysis and visualization for the sciences	database management
Zia et al. [595]	reduction of driver stress in motorway merging solutions	ambient intelligence
Holford et al. [231]	self-defending object in security-aware applications	information security
Gönczy et al. [185]	testing of infrastructure components	testing
Musil et al. [384]	facilitating heterogeneous team collaboration through flexible processes	process improvement
You et al. [576]	intelligent smart home by community computing	ambient intelligence
Skoutas et al. [496]	natural language representation of requirements for ETL processes	data warehouse
Jurado et al. [265]	collaborative tasks of a CSCL environment	cooperative design
Seater et al. [474]	requirements progression in problem frames	requirements engineering
Lee et al. [316]	gesture-based interface for elderly in smart home	ambient intelligence
Sun et al. [509]	scheduling strategy for data stream management	web management
Luotsinen et al. [337]	evaluation of agency paradigms	AOSD
Mistrzyk et al. [375]	task models for operations charts in industrial production	information environments
Hariz et al. [213]	service abstraction model for dynamic user interface presentation	pervasive computing
Yu et al. [577]	evolving self-organizing software systems	applied intelligence
Bomarius et al. [50]	learning software organizations with experience factories	process improvement
Zaremba et al. [579]	b2b mediation and discovery scenarios	semantic web
Dadam et al. [116]	adaptive process-aware information systems	e-business
van de Ven et al. [537]	regulation drafting and semantic web	computable models
Riahi et al. [447]	XML in generation of mobile HCI	HCI
Noguero et al. [399]	proactive nodes for scheduling distributed embedded systems	network applications
Tan et al. [515]	agent-augmented co-space	autonomic computing
Walczak et al. [547]	augmenting agents with deliberative planning techniques	multi-agents
Basapur et al. [36]	user expectations from dictation on mobile devices	HCI
Martinez et al. [355]	securing RFID-enabled banknotes	financial cryptography
Ruiz et al. [460]	simulation environment for intelligent manufacturing systems	multi-agents
Meier [365]	attacker modeling	security protocols
Mylopoulus [387]	quality and value-based requirements engineering	requirements engineering
Chen et al. [84]	positioning for GSM phones	ubiquitous computing
Parulek et al. [411]	problem solving environment for stereology-based modeling applications	internet
Hatebur et al. [217]	requirements analysis of dependable software	reliability
Sandberg et al. [466]	model-based safety engineering in automotive vehicles	automotive safety
Mene'ndez et al. [367]	parallel implementation of a neural network training application	internet
Wu et al. [566]	enterprise application architecture	enterprise architecture
Di Napoli et al. [132]	service control mechanism for grid scheduling	internet
Hawryszkiewycz [219]	lightweight platforms for complex adaptive processes	pervasive computing
to be continued …		

Author and reference	Topic	Domain
Gardelli et al. [172]	simulations in engineering self-organizing systems	self-organizing systems
Cardellini et al. [74]	self-adaptation for dependable service-oriented systems	dependable systems
Salehi et al. [464]	load balancing in agent-based grid	distributed computing
Enderle [147]	robotics and mechatronics kit	robotics
Simko et al. [597]	adaptive web-based learning	knowledge society
Sakellariou et al. [463]	augmented reality environment for complex anatomy training	virtual reality
Zeng [580]	pseudonymous PKI for ubiquitous computing	public key infrastructure
Eavis et al. [141]	compression architecture for data warehouse environments	data warehouse
Caballe et al. [66]	collaborative learning process in distributed environments	service-oriented computing
Choi et al. [94]	usability evaluation of ubiquitous computing devices	HCI
Nowostawski et al. [402]	dynamic environment experiments with evolvable virtual machines	self-organizing systems
Pfeifer et al. [427]	information theoretic implications of embodiment	artificial intelligence
Kwok et al. [305]	security modeling for risk analysis	security in information
Malatesta et al. [348]	mimicking the human brain with neural network retraining	artificial intelligence
Reichert et al. [443]	preservation of interactive environments and workflows	digital libraries
Gortz [202]	safety and progress properties with RSL	formal methods
Sjouw et al. [495]	TCP behavior on transatlantic lambdas	grid computing
Raybourn [442]	cultural representation in community-based virtual environments	universal access
Tudorache et al. [529]	collaborative ontology development	semantic web
Tang et al. [516]	goal-directed modeling of self-adaptive software architecture	information systems
Lee et al. [312]	interface design technique	HCI
Holvoet et al. [233]	coordinating agents intentions	multi-agents
Hetzner et al. [227]	self-regulated learning through linking experience	ubiquitous learning
Hazzan et al. [220]	introduction to agile software engineering	agile SE
Das et al. [121]	database technologies for RDF	semantic web
Song et al. [503]	formal reasoning about specification-based intrusion detection	security
Chung et al. [98]	software and systems architecture	software architecture
Becker et al. [38]	generation of performance prototypes	performance
Eberle et al. [142]	scopes for robust workflow in pervasive environments	service-oriented computing
Jimenez-Peris et al. [263]	architectural patterns for service-oriented infrastructures	dependability
Ribeiro et al. [448]	fuel cell system simulation for telecommunication	simulation
Lin et al. [324]	quantifying the influences of imperfect debugging	simulation
Alonso et al. [15]	safe tele-operated robots	reliability
Tunstall et al. [531]	inhibiting card sharing attacks	information security
Machulak et al. [341]	dependable access control systems	dependability
Ryan [461]	confidence issues with voting technologies	formal methods
Chung et al. [99]	system and software architecture challenges	software architecture

3.4 Science Direct

Included results are in Tab. 3.8, excluded results in Tab. 3.9.

Table 3.8: Included Results from Science Direct

Author and reference	Date	Pub.	Type	Topic	Domain	Benefit
Abdulaziz et al. [4]	2011	A	review	car parking requirements for sustainable transport development	transport	s app dom
Alain et al. [11]	2006	A	method	modeling living systems, their diversity and their complexity	agronomy systems	s app dom
Alexandrov [13]	2011	L	assessment	technical assessment and evaluation of environmental models	environmental modeling	s concept
Ashraf et al. [29]	2012	A	method	image data fusion for the remote sensing of freshwater environments	applied geography	s app dom
Beusen et al. [43]	2011	A	tool	dynamic simulation and visualization software for mathematical models	environmental modeling	s SW sol
Bovea et al. [56]	2012	A	tool review	taxonomy of ecodesign tools for integrating environmental requirements	clean production	S in SE
Brown et al. [60]	2010	A	tool	software tool designed to verify ensemble forecasts of numeric variables	environmental modeling	s SW sol
Cardona et al. [75]	2011	A	model	software package developed for dynamic simulation of water quality in rivers	environmental modeling	s SW sol
Cui et al. [110]	2009	A	method	management-oriented valuation for ecol. water requirements for wetlands	nature conservation	s app dom
Faith-Ell et al. [151]	2006	A	case study	application of environmental requirements in Swedish road maintenance contracts	cleaner production	s app dom
Fan et al. [153]	2007	A	model	model for China's energy requirements and CO2 emissions analysis	energy	s app dom
Fuller et al. [168]	2006	A	tool	software package for optimizing connectivity in conservation planning	biodiversity protection	s SW sol
Harmon et al. [214]	2009	A	evaluation	exploratory evaluation of the market case for green energy	green energy	s app dom
Hughes et al. [241]	2010	A	framework	determination of environmental water requirements for rivers	environmental modeling	s app dom
Justyna et al. [266]	2010	A	review	green roof performance towards management of runoff water quantity and quality	ecological engineering	s app dom
Kalivarapu et al. [272]	2008	A	framework	software framework for modeling of contaminant transport in groundwater	environmental modeling	s SW sol
Kit et al. [285]	2012	A	tool	texture-based identification of urban slums in India using sensing data	applied geography	s SW sol
Koormann et al. [295]	2006	A	model	modeling down-the-drain chemicals in rivers	environmental modeling	s concept
Kubba [299]	2010	BC	strategy	green project requirements and strategies	architecture	s concept
Liu et al. [326]	2011	A	study	energy requirements and carbon dioxide emissions of tourism industry	energy	s app dom
Mei et al. [364]	2010	A	review	research progress of ecological water requirement in china	ecological informatics	s app dom
Naumann et al. [395]	2011	A	model	reference model for green and sustainable software and its engineering	software engineering	S in SE
Rizzo et al. [450]	2006	A	evaluation	dynamic systems-based software packages for ecological systems	environmental modeling	s SW sol
Smith et al. [499]	2010	CP	method	green product design through product modularization using atomic theory	lean manufacturing	s concept
Tong et al. [525]	2011	A	method	generating the plan of mandatory green space in urban systems	urban development	s app dom
Tseng et al. [528]	2010	A	study	evaluating a firm's green supply chain management	cleaner production	s app dom
Xu et al. [568]	2010	A	review	review on ecological engineering based engineering management	management	s concept
Yen et al. [574]	2011	A	study	management's role in adopting green purchasing standards in industry	business research	s concept
Zhang et al. [584, 585]	2011	A	study	costs and barriers of green property development in China	property development	s app dom
Zhang et al. [586]	2010	A	model	multi-source remote sensing data for estimating ecological water requirement	environmental modeling	s SW sol

Publications on environmental modeling were included when software systems are needed for supporting processes.

Table 3.9: Excluded Results from Science Direct

Author and reference	Topic	Domain
Alrajeh et al. [16]	abduction and induction for operational requirements elaboration	inductive logic programming
Ameli et al. [19]	simulation of a micro-turbine based CHP system	thermal engineering
Andrade et al. [23]	lessons learned system for critical software	reliability engineering
Andrea et al. [24]	performance measurement systems and their relation to strategic learning	accounting
Beecham et al. [39]	systematic literature review on motivation in software engineering	SE
Birgit et al. [46]	sound insulation regulation requirements between dwellings	applied acoustics
Bodin et al. [49]	threonine requirements for rainbow trout and atlantic salmon	aquaculture
Boness et al. [51]	method for assessing confidence in requirements analysis	requirements engineering
Booth et al. [53]	digestible protein and energy requirements of yellowtail kingfish	aquaculture
Boulos et al. [54]	software agents to preserve individual health data confidentiality	biomedical informatics
Breaux et al. [58]	legally "reasonable" security requirements	requirements engineering
Bush [65]	software, regulation, and domain specificity	software engineering
Burger-Helmchen et al. [63]	typology of users in the video game industry	social software
Cai et al. [68]	link between software testing and system dynamics	software testing
Capra et al. [73]	related development environments to software energy efficiency	green IT
Casper et al. [79]	high resolution maps for heterogeneity of water quality in rivers	applied geography
Chen et al. [81]	tool support for conducting senior projects in software engineering	education
Chen et al. [83]	empirical analysis of development problem factors on software maintainability	maintainability
Christian et al. [96]	scenario-driven approach to evaluate performance and efficiency	product lines
Chun [97]	undetected software errors via the correlated capture–recapture model	operational research
Coleman et al. [101]	selection and usage of grounded theory for assessing SPI	process improvement
Comino et al. [104]	dual licensing in open source software markets	open source software
Corbin et al. [105]	knowledge management scheme for software engineering support	knowledge management
Cornelia et al. [106]	dynamics in innovation systems for game software	innovation systems
Dan et al. [120]	horizontal technology policies and industry-state co-evolution	research policy
David et al. [122]	who is the community of developers of open-source software	open source software
DelaPeyronnie et al. [128]	modernization of the Eurocat Air Traffic Management System	information systems
Deng et al. [129]	dietary protein requirement of juvenile Asian red-tailed catfish	animal feed science
Dong et al. [135]	corrosion behavior of epoxy/zinc duplex coated rebar	construction materials
Elferink et al. [143]	land requirements for meat production	agricultural production
Elish et al. [144]	predicting defect-prone software modules using support vector machines	software metrics
to be continued ...		

Author and reference	Topic	Domain
Feichtinger et al. [157]	software design for computational engineering simulations	supercomputers
Ferrari et al. [158]	gauging the progress of Software Architecture research	software architecture
Ferrari2008 et al. [159]	architecting-problems rooted in requirements	software architecture
Fox et al. [163]	case study of land cover change and runoff	applied geography
Frankova et al. [164]	business processes with service level agreements from early requirements	business processes
Fuh et al. [167]	adsorption effect induced by elliptically polarized light	liquid crystal
Gil et al. [180]	heat transfer and inactivation kinetics of microorganisms on food surface	food engineering
Giuri et al. [183]	skills, division of labor and performance in collective inventions	open source software
Gong et al. [186]	land suitability evaluation for development	land use policy
Gong et al. [187]	measurement of theanine using ion-pair liquid chromatography	food chemistry
Gorschek et al. [190]	dependent variables of requirements engineering	requirements engineering
Gorschek et al. [191]	empirical evaluation of a requirements abstraction model	requirements engineering
Grimstad et al. [195]	software effort estimation terminology	software effort estimation
Grisdale-Helland et al. [196]	efficiency of lysine utilization for growth of Atlantic cod	aquaculture
Groenesteijn et al. [197]	office task effects on body dynamics in five dynamic office chairs	applied ergonomics
Grudpan et al. [199]	analytical procedures for acidity and iron assays	natural reagents
Hanssen et al. [210]	industrial case study on agile software product line engineering	software product lines
Hanssen [211]	longitudinal case study of an emerging software ecosystem	software engineering
Harary et al. [212]	3D Euler spirals for 3D curve completion	computational geometry
Hartmann et al. [215]	changing industry structure of software dev. for consumer electronics	industry structures
Hashem et al. [216]	green-house cover on evapotranspiration and cucumber water requirements	agriculture
Hauge et al. [218]	systematic literature review on adoption of open source software	open source software
Hazzan et al. [221]	human-related measures support software development processes	human aspects
Hoest [3]	systematic review of research on open source software	open source software
Holme et al. [232]	development of a formulated microbound diet for mud crab	aquaculture
Hoorn et al. [235]	business needs: fears dictate the must haves; desires the won't haves	requirements engineering
Hosek et al. [236]	system for optical coherence tomography	laboratory automation
Hsiung et al. [237]	verification of real-time embedded software for ubiquitous systems	embedded systems
Huang et al. [238]	cost and reliability of modular software systems in the testing phase	software testing
Huang et al. [240]	software version management based on a interface dependency matrix	component-based software
Forster [162]	dietary requirements of fish under culture conditions	fish
Van Saun [467]	nutrient requirements of South American camelids	american camelids
Jadhav et al. [247]	framework for evaluation and selection of the software packages	software evaluation
Jaiswal et al. [248]	evaluation of colour, polyphenols and antioxidant capacity of cabbage	food chemistry
James et al. [249]	economics of open source software development	open source software
Janzen et al. [253]	evidence-based SE through a community-driven web database	software engineering
Jarabo et al. [254]	agricultural residues used as a source of fibres	industrial crops
Jarke et al. [257]	principles that underlie contemporary requirements processes	requirements engineering
Jiao et al. [262]	assembly of Internet-scale software systems involving agents	autonomous agents
Kari et al. [455]	interaction and reality construction in software engineering	human aspects
Karlsson et al. [274]	interview study on RE challenges in market-driven software development	requirements engineering
Kastner et al. [277]	land requirements for food in the Philippines	land use policy
Kazman et al. [279]	scaling up software architecture analysis	software architecture
Kilamo et al. [281]	open source software as platform for software ecosystems	open source software
Kim et al. [282]	recycled paper sludge and biomass materials in composite pallet	resources and recycling
Ko et al. [290]	classification techniques for informal requirements	requirements engineering
Koch [291]	effort modeling and programmer participation in open source software	open source software
Koong et al. [294]	testing environment for multi-core embedded software	software testing
Krishnamurthy et al. [298]	monetary donations to an open source software platform	research policy
Kuo et al. [303]	irrigation water requirements with derived crop coefficients	agriculture
Lai et al. [307]	ranking of customer requirements in a competitive environment	requirements engineering
Land et al. [308]	software systems in-house integration strategy selection	software integration
Li et al. [321]	software development team flexibility antecedents	team collaboration
Liebl et al. [323]	acoustic and visual distraction on cognitive performance and well-being	applied ergonomics
Liu et al. [332]	priority of software process requirements from multiple perspectives	software processes
Mostafa2011 [380]	neuro-computational intelligence analysis of software piracy rates	expert systems
Magdaleno et al. [342]	systematic review of software development models	software engineering
Magne et al. [343]	forecasting of software development work effort	forecasting
Mai et al. [347]	dietary choline requirement for juvenile cobia	aquaculture
Mellado et al. [366]	security requirements engineering framework for software product lines	software product lines
Miller et al. [371]	control-theoretic approach to the software system test phase	software testing
Mohagheghi et al. [376]	sys. lit. review on modeling quality in model-based software development	software quality
Muccini et al. [382]	software architecture-based regression testing	software testing
Myers et al. [386]	phosphorus maintenance requirement of lactating Holstein cows	agriculture
Nagase et al. [390, 389]	plant growth in extensive green roofs	urban landscape
Nakagawa et al. [393]	aspect-oriented reference architecture for SE environments	software engineering
Needham et al. [397]	software fault tree key node metric	software metrics
Ozkaya et al. [406]	computer-aided requirement traceability in architectural design	requirements traceability
Peng et al. [416]	evolution of variability in a software product line	software product lines
Peres et al. [421]	efficiency of lysine utilization in turbot	aquaculture
Petersen et al. [422]	software process improvement through lean measurement	lean software dev.
Petri et al. [423]	lessons from agile manufacturing for agile software product dev.	agile software dev.
Pettersson et al. [426]	light weight software process assessment and improvement planning	process improvement
Punter et al. [433]	transferring software engineering technology innovation	technology transfer
Purdon et al. [434]	system for acquisition and real-time processing of electrophysiology	neuroscience
Rafique et al. [436]	reusable software components for accelerator-based clusters	accelerator-based software
Ramasubbu et al. [438]	effect of employee skills and customer heterogeneity on customer satisfaction	decision support
Ray et al. [441]	design verification for embedded software systems	software engineering
Reisner et al. [444]	software system for processing, analyzing, and classifying Raman spectra	laboratory systems
Rexfelt et al. [446]	progress of user requirements through a development project	user requirements
Rohm et al. [453]	floor polish meets green seal requirements	surfactants
Rombach et al. [454]	teaching disciplined software development	education
to be continued …		

Author and reference	Topic	Domain
Rossitza et al. [457]	technological forecasting and social change	technological capabilities
Rowan et al. [458]	sediment fingerprinting as an environmental forensics tool	applied geography
Ruiz et al. [459]	heat requirements of apricot cultivars for flowering	botany
Ruokolainen et al. [2]	market domain model for start-up software technology companies	engineering management
Santos Soares et al. [137]	requirements modeling and analysis of software-intensive systems	requirements engineering
Savory et al. [468]	optoelectronic sensor for the monitoring of mould growth	building construction
Şen et al. [476]	acquiring enterprise software selection requirements	software selection process
Senyapili et al. [478]	software model for interior architecture	interior architecture
Shao et al. [481]	phosphorus requirement of juvenile black seabream	aquaculture
Sharp et al [485]	physical artefacts in agile software development	agile software dev.
Shen et al. [486]	PSP effect in training disciplined software development	personal software process
Shrestha et al. [488]	land fragmentation due to rapid urbanization	applied geography
Silva et al. [115]	6 years of systematic literature reviews in software engineering	systematic reviews
Sowe et al. [504]	knowledge brokers that yield software engineering knowledge	open source software
Stringfellow et al. [506]	software architecture reverse engineering methods	reverse engineering
Sutcliffe et al. [510]	requirements analysis methods for developing component libraries	requirements modeling
TechNews [511]	filter media meets 'green' building requirements	filtration
Tittelboom et al. [522]	acoustic emission analysis for autonomous crack healing	construction materials
Ullah et al. [533]	decision support for moving from a single product to a portfolio	software product lines
Valerdi et al. [536]	impact and contributions of MBASE on SE graduate courses	software engineering
Vavpotic et al. [541]	concurrent evaluation of technical and social aspects of software dev.	human aspects
Vinod et al. [545]	safety critical software system in probabilistic safety assessment	nuclear engineering
Walt et al. [548]	research results from free/open source software development	open source software
Wriedt et al. [565]	estimating irrigation water requirements in Europe	agriculture
Yang et al. [573]	environmental flow requirements for integrated water resources allocation	numerical simulation
Zaidan et al. [578]	biocatalytic production of lactose ester	food chemistry
Zhao et al. [587]	comparison of institutional systems affecting software advancement	technology in society
Zhong et al. [589]	epigallocatechin gallate derivatives and their antioxidant potential	food chemistry
Zhu et al. [429]	agents in agricultural expert system inspection software	agriculture
Zhu et al. [594]	aspect-oriented framework for building intrusion-aware software systems	AOSD

3.5 Web Of Science

Included results are in Tab. 3.10, excluded results in Tab. 3.11.

Table 3.10: Included Results from Web Of Science

Author and reference	Date	Pub.	Type	Topic	Domain	Benefit
Alvarez et al. [17]	2011	A	method	decision making for treatment intensity in purifying plants	wastewater	s app dom
Balana et al. [32]	2011	A	review	cost-effectiveness analysis of agri-environmental measures	water pollution	s app dom
Boose et al. [52]	2007	CP	method	reliable datasets for environmental models with an analytic web	ecological data sets	s SW sol
Bravi et al. [57]	2011	A	assessment	life cycle assessment of a micromorph photovoltaic system	energy	s app dom
Ellison et al. [146]	2006	A	model	analytic webs support the synthesis of ecological data sets	ecological data sets	s SW sol
Greene et al. [194]	2010	A	method	decision analysis with exploration and evaluation phases	land management	s app dom
Hall et al. [206]	2011	A	method	requirements for 3D vegetation structure from space	environmental modeling	s SW sol
I-Wah [243]	2011	A	analysis	development and conditions of home-school cooperation	education	s concept
Jia et al. [260]	2011	A	case study	urban wetland planning in Beijing	ecological complexity	s app dom
Jin et al. [264]	2011	A	study	integrated calculation of ecological water demand for basin systems	water demand	s app dom
Kaduk et al. [268]	2011	A	method	redicting the time of green up in temperate and boreal biomes	climate change	s app dom
Lundy et al. [336]	2011	A	method	integrating sciences to sustain urban ecosystem services	geography	s concept
McCabe [359]	2006	A	overview	sustainable building design in Australia	eco-architecture	s app dom
McIntosh et al. [361]	2007	A	method	database design for ecologists including observation data	ecoinformatics	s SW sol
Scheller et al. [471]	2010	A	method	increasing the reliability of ecological models using SE techniques	software engineering	S in SE
Seppala et al. [479]	2011	A	assessment	greenhouse gas emissions and material flows in Finland	clean production	s app dom
Singh et al. [494]	2011	A	method	resource conservation technology in rice-wheat cropping system	environment	s app dom
Tao et al. [517]	2008	CP	model	UML-based green alignment selection decision making model	intelligent computation	S in SE
Verweij et al. [543]	2010	A	perspective	IT perspective on integrated environmental modeling	software engineering	S in SE
Wang et al. [549]	2008	CP	method	systematic research on the cost control of the green industry	cost control	s concept
Wang et al. [553]	2009	CP	tool	web-based distributed certification system of green food	env. science	s SW sol
Xu et al. [567]	2007	A	evaluation	sustainability evaluation of a nature reserve project	environmental management	s app dom
Zhang et al. [582]	2011	A	assessment	combined biostabilization and landfill for solid waste	environmental management	s app dom
Zhou et al. [591]	2008	CP	method	green remanufacturing engineering in structural machinery	security technology	s app dom

Table 3.11: Excluded Results from Web of Science

Author and reference	Topic	Domain
Ambrosini et al. [18]	multi-hit hypothesis of primary biliary cirrhosis	immunology
Bakalov et al. [31]	high performance network models in a multiuser environment	transportation networks
Barboutis et al. [35]	energy requirements of Garden Warblers migrating across the Sahara	bird migration
Bennion et al. [40]	diatom records to establish reference conditions for lakes	water management
Berriman et al. [41]	software sustainability at the Infrared Processing and Analysis Center	software sustainability
Cammarano [70]	co-dominance and succession in forest dynamics	forestry
Casado et al. [77]	aryl hydrocarbon receptor activation in hematopoietic progenitor cells	molecular pharmacology
Casas et al. [78]	latitudinal adaptation in Spanish barleys	applied genetics
Cheng et al. [86]	experiments on waveform inversion of an internal solitary wave	fluid mechanics
Chin et al. [90]	sustainable ICT education ecosystem	education
Costa et al. [107]	oxidative stress protection of trypanosomes	parasitology
Davidar et al. [124]	extent and causes of forest degradation in India	forestry
Di Crescenzo et al. [131]	anonymity notions and techniques for public-key infrastructures	vehicular networks
Dong et al. [136]	software design of cloth design and simulation system	industrial design
Estrin [148]	applications and architecture for participatory sensing	internet
Fairless et al. [150]	deconstructing sociability in mouse models	evolutionary biology
Fallahi et al. [152]	effects of daphnia magna fed with vitamin-enriched chlorella	food enrichment
Fang et al. [154]	trustworthiness analyzing of interacting business process	trustworthiness
Fisher et al. [161]	business sustainability and undergraduate management education	education
Gary et al. [173]	agile methods for open source safety-critical software	open source software
Gehrkre et al. [175]	biotic and abiotic explanations for differences in lineage sizes of sedges	species richness
Germer et al. [177]	response of grain sorghum to fertilisation with human urine	field crops
Ghafoor et al. [178]	growing rice and wheat crops during reclamation of tile drained soils	irrigation
Giese et al. [179]	modular execution of reconfigurable hybrid systems	simulation
Gironi et al. [182]	LCA of polylactic acid and polyethylene terephthalate bottles	biodegradation
Grudpan et al. [198]	green analytical procedures for acidity and iron assays	natural reagents
Haezendonck et al. [204]	lobby-effect of port competitiveness' determinants	stochastic
He et al. [222]	pervasive health monitoring systems with body sensor networks	mobile computing
Helliwell et al. [225]	evolution of vitamin B(12) auxotrophy	biology
Hong et al. [234]	user acceptance of agile information systems	information systems
Hyde et al. [242]	measuring low-loss materials	measurement science
Idris et al. [244]	sequential injection chromatography for separation of propranolol	chemistry
Jarke et al. [256]	principles that underlie contemporary requirements processes	requirements engineering
Kalibera et al. [271]	scheduling real-time garbage collection on uniprocessors	joint scheduling
Kartseva et al. [275]	control patterns in a health-care network	information systems
Khatri et al. [280]	dyeing method for cotton fabric dyeing using ultrasonic energy	reactive dyes
Kim et al. [284]	video stabilization for CMOS image sensors	video technology
de Kok et al. [125]	decision-support system for integrated river-basin management	water resource management
Krever et al. [296]	rule of law and the world bank's development model	law
Krishna et al. [297]	solid lubricants in machining	mechanical engineering
Lank et al. [310]	user centred rapid application development	software engineering
Larned et al. [311]	flow variation down the lengths of alluvial rivers	river ecohydrology
to be continued ...		

Author and reference	Topic	Domain
Leonhardt et al. [317]	cuticular profiles of Australian stingless bees	ecology
Lindbladh et al. [325]	landscape and policy perspective on forest conversion	forestry
Lutz et al. [338]	software engineering for space exploration	software engineering
Lye et al. [339]	efficacy of artificial domiciles for bumblebees	nature conservation
McCarty et al. [360]	development and testing of a dynamic scheduling system	astronomy
Mei et al. [363]	internetware as software paradigm	software engineering
Miller et al. [370]	agent for the prevention of type 1 diabetes	biological therapy
Missaoui et al. [374]	formal concept analysis for data warehouses	data warehouses
Mohammadi et al. [378]	sustainable soil fertility system for chickpea	biotechnology
Nadell et al. [388]	fitness trade-off between local competition in cholerae biofilms	bacteria evolution
Nakagawa et al. [392]	aspect-oriented reference architecture for SE environments	AOSD
Nordentoft et al. [400]	real-time detection and identification of chlamydophila species	microbiology
Onishi [403]	impact of CO2 emissions on the world economy policy simulations	policy modeling
Oshaghi et al. [404]	mitochondrial DNA diversity in the populations of great gerbils	species identification
Pan et al. [408]	effect of gold content on the reliability of solder joints	manufacturing technology
Parsons et al. [410]	plant breeding for yield and persistence	grass and forage
Pathania et al. [412]	fodder supply from public and private lands	animal sciences
Patil [413]	monograph for observational economy in environmental studies	ecological statistics
Peanne et al. [415]	effects of Conserved Oligomeric Golgi on galactosyltransferase	glycobiology
Perderau et al. [419]	termite competition between invasive and indigenous species	biological invasions
Patter et al. [425]	design science based evaluation framework for patterns	information systems
Phillips et al. [428]	mycorrhizal symbioses cause rarity in orchids	ecology
Rao et al. [440]	climate change impact on crop water requirements in arid Rajasthan	agrometeorology
Ricci et al. [449]	environment programming in multi-agent systems	mutli agents
Robin et al. [452]	determining the sex of a monomorphic threatened passerine	biology
Saad et al. [462]	hedonic coalition formation for distributed task allocation	agents
Schiel et al. [472]	comparable measurement under the European water framework directive	water management
Seitz et al. [475]	science in river systems cumulative effects assessment practice	env. impact assessment
Sen et al. [477]	EGCG downregulates EGF-induced MMP-9 in breast cancer cells	nutrition
Sethi et al. [480]	optimal crop planning and water resources allocation	agriculture
Singh et al. [492]	effect of feeding different levels of cereal green fodder	animal nutrition
Singh et al. [493]	review of microalgae as second generation biofuel	agronomy
Sternberg et al. [505]	virulent parasite provides protection against a lethal parasitoid	infection genetics
Sujit et al. [508]	self assessment-based decision making for multiagent search	multi agents
Wang et al. [550]	add-on feedforward compensation for vibration rejection in HDD	mechatronics
Warner et al. [556]	PXL-1 for pharyngeal muscle contraction and for viability	molecular biology
Wongthongtham et al. [564]	social network based approach for software engineering ontology	software engineering
Yamada et al. [570]	quantitative evaluation of liver function	radiology
Yan [571]	discrete Fourier transform of three-dimensional interacting electron gas	physics
Yan et al. [572]	autonomic trust management for a component-based software system	secure computing
Zhao et al. [588]	energy consumption of CO(2) regeneration process	chemistry

3.6 Results for the Research Questions

What is the current state of the art in supporting sustainability in software engineering research and practice? We discuss the research questions posed in Sec. 1.2.

3.6.1 How much activity was there in the last 20 years (1991-2011)? (RQ 1)

We summarized the number of relevant publications per database in Tab. 3.12, per year in Tab. 3.13, and per publication type in Tab. 3.14. 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 simply included as they were fully available.

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

Table 3.12: Results General Activity: 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 3.13: Results General Activity: 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 3.14: Results General Activity: 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

3.6.2 What research topics are being addressed? (RQ 2)

Figure 3.1: Weighted topic keyword cloud, created with http://www.wordle.net/

For a quick illustrated overview, we have generated a weighted topic cloud from keywords we chose from the titles and abstracts (Tab. 3.2-3.10) that visualizes the topics in Fig. 3.1.

We have derived a taxonomy for the addressed research topics in Fig. 3.2 that abstracts from some of the details listed in the original classifications tables in Tab. 3.2-3.10.

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.

3.6.3 What are the limitations of current research? (RQ 3)

To identify limitations of current research, we reviewed our classification of topics and applications domains in Tab. 3.2-3.10. We performed a pragmatic and informal gap analysis that resulted in three major limitations:

Table 3.15: Results General Activity: Venues and Journals

Issue	Name
Conferences & Workshops	IEEE International Symposium on Sustainable Systems and Technology (ISSST)
	Digital EcoSystems and Technologies Conference
	Intl. Conf. on e-Business Engineering
	International Conference on Security Technology
	High performance computing
	European Conference on Artificial Intelligence
	Conference on Software Engineering Education & Training
	Intl. Conf. on Digital Manufacturing & Automation
	Intl. Conf. on Online communities & social computing
	Intl. Conf. on End-user development
	Intl. Conf. on Digital government research
	Intl. Conf. on Human factors in computing systems
	Intl. Conf. on Infrastructure for Collaborative Enterprises
	Intl. Conf. on System science and simulation in engineering
	Intl. Conf. on Fuzzy Systems
	IASTED Intl. Conf. on Modelling and simulation
	ACM conference on Computer supported cooperative work
	Intl. Conf. on Internationalization, design and global development
	Euro-Par 2006 Parallel Processing
	Computer And Computing Technologies In Agriculture
	Intl. Conf. on Ecological Informatics and Ecosystem Conservation
	Intl. Conf. on Flexible Automation and Intelligent Manufacturing
	Intl. Conf. on Intelligent Computation Technology and Automation
	Conference on Industrial Cluster Development and Management
	Intl. Conf. On Environmental Science and Information Application Technology
Books	The Future Internet
	Game-based Education System Design and Development
	Green Construction Project Management and Cost Oversight
Journals	Environmental modeling & Software
	Computers & Geosciences
	Intelligent Data Analysis
	International Journal of Metadata, Semantics and Ontologies
	Information Technology and Management
	Expert Systems with Applications
	International Journal of Mobile Learning and Organisation
	Journal of Intelligent Information Systems
	Computers and Electronics in Agriculture
	Journal of Strategic Information Systems
	Simulation and Gaming
	WSEAS Transactions on Computers
	SIGMETRICS Performance Evaluation Review
	Comptes Rendus Biologies
	Applied Geography
	Journal of Cleaner Production
	Journal for Nature Conservation
	Technological Forecasting and Social Change
	Renewable and Sustainable Energy Reviews
	Sustainable Computing: Informatics and Systems
	Computers, Environment and Urban Systems
	Omega
	Journal of Business Research
	Building and Environment
	Ecological Economics
	Ecological Informatics
	Energy
	Ecology
	Forest Ecology and Management
	Remote Sensing of Environment
	Asia-pacific Education Researcher
	Ecological Complexity
	Science China technological Sciences
	Climatic Change
	Progress In Physical Geography
	Eco-Architecture: Harmonisation between Architecture and Nature
	Frontiers In Ecology and the Environment
	Research Journal of Chemistry and Environment
	Ecological Modelling
	Journal on Environmental Management

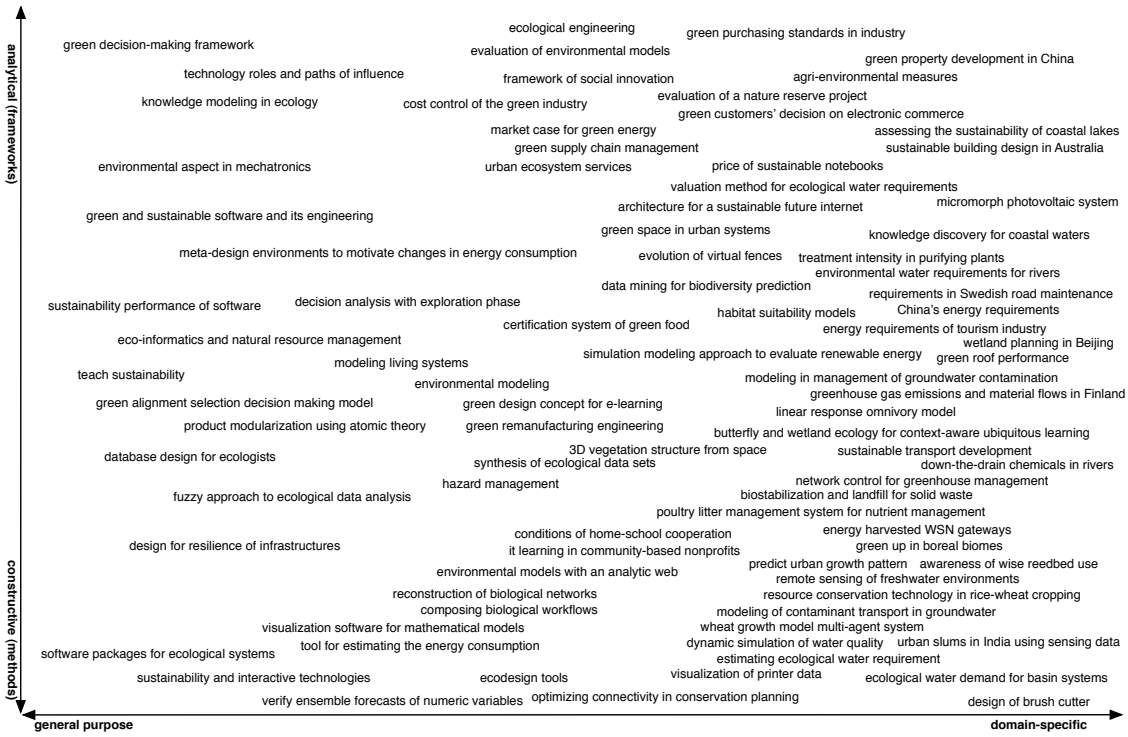

Figure 3.2: Taxonomy of research topics

- *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., [417] and decision support systems, e.g., [239].
  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 [362].

- *High domain-specifity.*
  Reason: The frameworks and methods we found within the results are highly domain-specific, e.g., [302, 592]. This is also visible in the higher density of domain-specific approaches in Fig. 3.2.
  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 [395].
  Conclusion: An encompassing reference framework is still missing.

3.6.4 How is sustainability support performed? (RQ 4)

Constructive support for sustainability is performed by frameworks, models, methods, and metrics (Tab. 3.16). Thereby, most approaches are specific to a special application domain, as visible by the density on the domain-specific side in Fig. 3.2.

Table 3.16: 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

- Frameworks, e.g., for civil engineering [302] or contaminant transport [272]
- Models, e.g., for software systems [395] or databases [112]

- Methods for specific application areas, e.g., security technology [592], green product design [499], or ecology knowledge [417]
- Metrics, e.g., for sustainability in eBusiness [12]

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.

3.6.5 Which methods are in use? (RQ 5)

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. [417], as means to represent their data, knowledge, or information models. Neural networks are in use for dynamic environments and simulations, e.g. [138]. Methods adapted from other disciplines are, inter alia, cost calculations, e.g. [439], and life cycle analysis, e.g. [57].

3.6.6 Are there case studies available? (RQ 6)

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. 3.17. 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 primary researcher.

Table 3.17: Case Studies

Author and ref.	Domain	Context	Applied method
Huang et al. [239]	web engineering	support green customers' decision process on electronic commerce	questionnaire and experiment
Faith-Ell et al. [151]	cleaner production	application of environmental requirements in Swedish road maintenance	semi-structured interviews
Liu et al. [326]	energy	energy requirements and carbon dioxide emissions of tourism industry	index decomposition analysis
Tseng et al. [528]	cleaner production	evaluating a firm's green supply chain management	relational analysis, experiment
Yen et al. [574]	business research	management's role in adopting green purchasing standards in industry	questionnaires
Zhang et al. [584, 585]	property development	costs and barriers of green property development in China	cost analysis
Jia et al. [260]	ecology	urban wetland planning in Beijing	ecological complexity research
Jin et al. [264]	hydrology	ecological water demand for basin systems	integrated calculation

3.6.7 Which domains are already considered? (RQ 7)

For an illustrated overview, please see the weighted domain cloud that visualizes the application domains in Fig. 3.3. We have derived a taxonomy for the domains that were used and described in the publications in Fig. 3.4. We used the same dimensions as for the research topics taxonomy in Fig. 3.2 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,

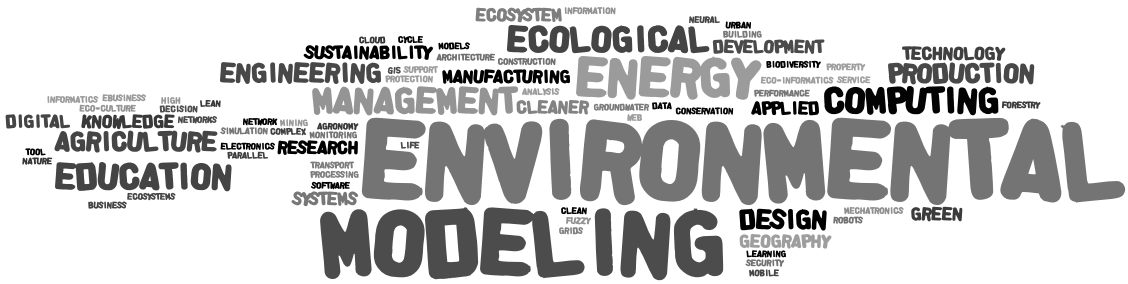

Figure 3.3: Weighted domain cloud, created with http://www.wordle.net/

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. 3.4 indicate the individual domains.

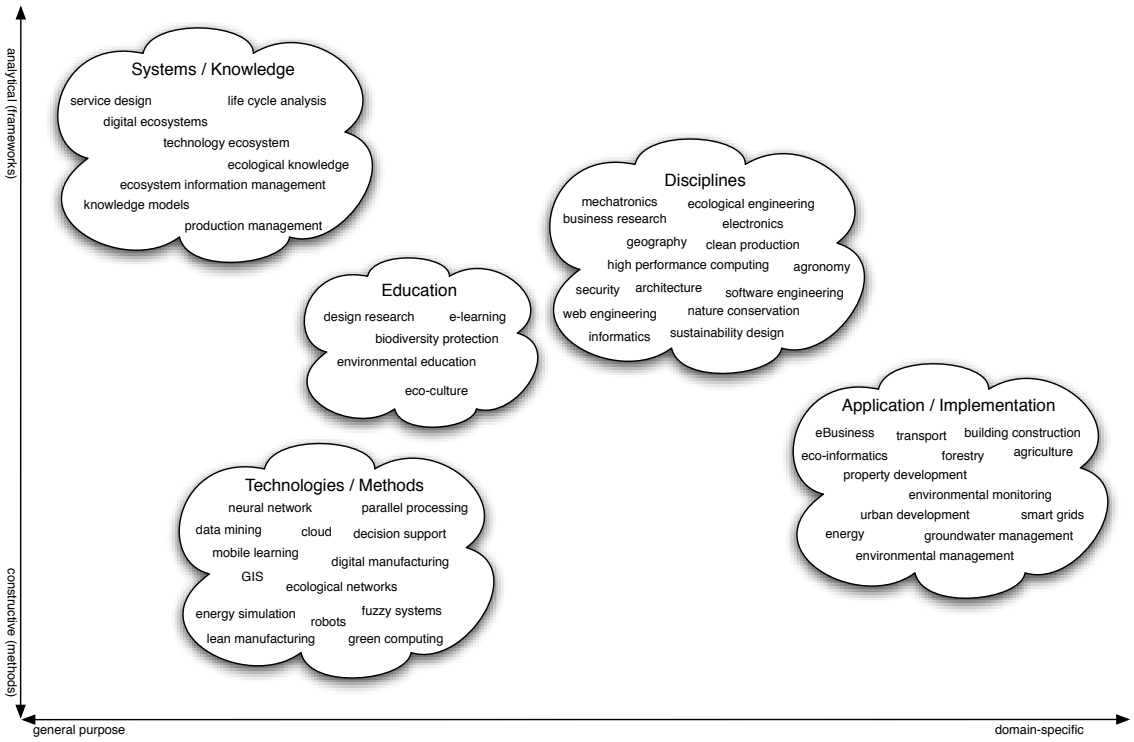

Figure 3.4: Taxonomy of application domains

4 Discussion

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

4.0.8 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. 3.2-3.10). As we found less than expected for a body of knowledge on *S in SE*, we decided to extend the inclusion into the results to publications that we classified as a research work 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 Chap. 3.

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.

4.0.9 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. 4.1.

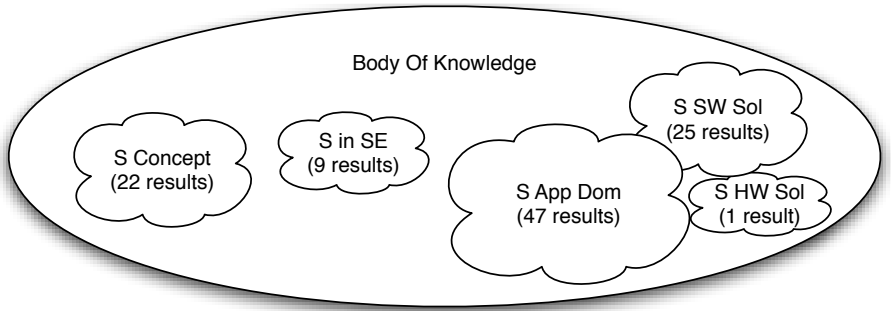

Figure 4.1: Areas of the Body of Knowledge for S in SE

4.1 Threats to Validity

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

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).

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:

- Purely hardware (GreenIT): As the automatically found Green IT publications all contained part of the second parenthesis of the search string, they were included in the results.
- Purely application in environmental domains: Here we found, for example, agricultural support systems with no explicit relation to sustainability. These systems would have been included, had they exhibited an explicit link to sustainability in their content.
- "Environment" meant in the sense of system environment, not nature: As the term can be used in both senses and there is no way to semantically distinguish the use in an automated search, these samples had to be excluded by hand.
- "Ecosystem" meant as population of interacting systems, for example, agents: As the term can be used in both senses and there is no way to semantically distinguish the use in an automated search, these samples had to be excluded by hand.
- Pure software engineering papers that are not specifically related to sustainability.

Indicators for too many relevant exclusions:

- 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 (more databases), 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 publications by Lorenz Hilty (e.g., [228]), who leads the research group for Informatics & Sustainability at the University of Zürich, and would have been considered relevant. However, Hilty is an expert rather on *informatics* in general and sustainability without an explicit emphasis on software engineering — and therefore it is appropriate that his publications did not show up in the results. Another paper we missed was Cabot et al. [67], as it treats goal modeling for supporting sustainability in the context of conference organisation. Mahaux et al. [345] were also missing in the results, with their work on exploring sustainability requirements.[1] Some other authors we expected (e.g., Naumann et al. [395]) did show up in the results.

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".

We did not test whether the order of the search string made a difference in the results, but 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.

Cross-validation of the search engines

We received hardly any double entries in the automatic search results. On one hand, this is little surprise as we chose three databases by specific publishers (IEEExplore, ACM and Springer) instead of meta search engines, on the other hand 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 increased the effort too much (due to highly redundant results, as a pre-check showed).

[1] 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 for sustainability in software engineering.

Interestingly, Web of Science found Estrin [148] 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.

5 Conclusions

In this report, we presented the results of our SLR 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.

6 Acknowledgements

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