Abstract—Despite the vast body of work on self-adaptation, no systematic study has been performed on the claims associated with self-adaptation and the evidence that exists for these claims. As such an insight is crucial for researchers and engineers, we performed a literature study of the research results from SEAMS since 2006 and the associated Dagstuhl seminar in 2008. The study shows that the primary claims of self-adaptation are improved flexibility, reliability, and performance of the system. On the other hand, the tradeoffs implied by self-adaptation have not received much attention. Evidence is obtained from basic examples, or simply lacking. Few systematic empirical studies have been performed, and no industrial evidence is reported. From the study, we offer the following recommendations to move the field forward: to improve evaluation, researchers should make their assessment methods, tools and data publicly available; to deal with poor discussion of limitations, conferences/workshops should require an explicit section on limitations in engineering papers; to improve poor treatment of tradeoffs, this aspect should be an explicit subject of reviews; and finally, to enhance industrial validation, the best academy-industry efforts could be formally recognized by the community.

I. INTRODUCTION

Self-adaptation is widely recognized as a key approach to tackle some of the hard challenges of engineering and managing complex distributed software systems [1], [2], [3]. Self-adaptation endows a software system with the capability to adapt itself to internal dynamics and dynamics in the environment in order to achieve certain goals. Examples are a system that heals itself when certain errors occur, or a system that optimizes its performance under changing conditions.

Different loosely connected communities have studied self-adaptation. Prominent examples are the SEAMS community (International Symposium on Software Engineering for Adaptive and Self-Managing Systems, http://www.self-adaptive.org/), the ICAC community (International Conference on Autonomic Computing, http://www.autonomic-conference.org/), and the SASO community (Self-Adaptive and Self-Organizing Systems, http://www.saso-conference.org/). The co-existence of different communities has led to the exploration of the field from different perspectives. However, it has also led to fragmentation of the field and the development of different vocabularies. In this paper, we take a broad perspective on what is considered as a self-adaptive system. In particular, we consider a self-adaptive system as a system consisting of two parts: a managed system and a managing system. The managed system is situated in an environment and provides some functionality to users. The managing system comprises the software to monitor the managed system and its environment and performs adaptations of the managed system when needed. Note that the software of the managed system and the software of the managing system may be clearly partitioned in separate modules or layers, or the software of the two parts may be interwoven.

A. Problem Description and Objectives

Over the last decade, researchers and engineers have developed a huge body of work on engineering self-adaptive systems. However, it is not clear how the research results have actually contributed to improvements of engineering complex software systems. Several survey articles have been written over the last years, e.g. [4], [5], [6], [7]. These articles summarize achievements of the field and outline challenges for future work. However, to the best of our knowledge, no systematic study has been performed on the claims associated with self-adaptation and the evidence that exists for these claims. As a result, there is no clear view on how self-adaptation actually contributes to tackling the challenges of engineering and managing complex software systems. However, such an insight is crucial for researchers and engineers. Our objective is to study and summarize existing research related to engineering self-adaptive software systems and shed light on what the claimed benefits are of self-adaptation and to what extent evidence exists for these benefits. In particular, we aim to:

1) identify the focus of current research in engineering self-adaptive systems, providing context for the study,
2) assess the quality of current research studies,
3) understand the claims made for self-adaptation and the available evidence for these claims, and
4) identify limitations of current approaches and outline potential areas for future work in the field, helping to derive conclusions from the study.

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From the study, we offer recommendations to move the field forward. We focus in this study on the research results of SEAMS since 2006 and the Dagstuhl seminar in 2008 (http://www.self-adaptive.org/). As such, the study will cover a representative sample of the literature, which allows deriving recommendations to move the field forward. However, a complete systematic literature review [8] is required to confirm whether the findings are conclusive for the whole field.

B. Paper Overview

In Section 2 we discuss the method we used in our study. We explain the research questions we address, discuss the criteria to assess the quality of studies, and summarize the data items that were collected. In section 3 we present the data extracted from the studies, and interpret this data answering the research questions. Section 4 discusses limitations of our study, compares our findings with related studies, and presents recommendations to move our field forward. Finally, we wrap up and conclude in section 5.

II. Research Method

Our study comprises the primary steps of a systematic literature review [8], which is a well-defined approach to identify, evaluate and interpret all relevant studies regarding a particular research question, topic area or phenomenon of interest. The major difference in comparison to a systematic literature review is that we restricted the scope of the study upfront, i.e, we studied the papers published at SEAMS between 2006 and 2011 and the papers of the 2008 SetSAS book (www.springer.com/computer/swe/book/978-3-642-02160-2). Since our primary goal is to understand the claims and supporting evidence of self-adaptation, we excluded papers about theoretical aspects, as well as surveys and roadmap papers. We also excluded short papers of 1 or 2 pages. Overall, we studied 96 papers out of a total of 124 papers. Figure 1 shows an overview of the three-phased method we applied in the study.

In total four researchers that are active in the field of self-adaptive systems and 45 master students\(^2\) were involved in the review. The review planning (Phase 1) was performed by the researchers. In particular, two researchers defined initial research questions, together with the data items that had to be collected. Two other researchers checked the questions and data items. The feedback was used to make small adaptations of questions and data items. Subsequently, the researchers supported by the master students conducted the review (Phase 2). Each study was assigned to two researchers and two groups of two students. For each study, we organized a 20 minutes discussion session where all assigned reviewers came together with the data they collected from the study. During these discussions sessions, a decision for each data item was taken, based on consensus. The data was then added to a database for subsequent analysis, which was performed by the researchers. Finally, the group of researchers prepared this final report (Phase 3).

All the material that was used for the study is available at http://homepage.lnu.se/staff/daweaa/SLR-SEAMS.htm.

In the remainder of this section, we present the research questions for the study, and summarize the quality assessment criteria and data items collected for the study. We also briefly explain how we performed data analysis.

A. Research Questions

We formulated the goal of the study through Goal-Question-Metric (GQM) perspectives (purpose, issue, object, viewpoint) [10]. The general goal of our study is:

**Purpose:** Understand and characterize

**Issue:** the claims and supporting evidence

**Object:** of self-adaptive software systems

**Viewpoint:** from a researchers and engineers viewpoint.

The general research question translates to several concrete research questions. In detail, our study covers the following research questions:

**RQ1:** What is the focus of research in self-adaptive software systems?

**RQ2:** What are the claimed benefits of self-adaptation and what are the tradeoffs implied by self-adaptation?

**RQ3:** What assessment methods have been used and how much evidence is available?

**RQ4:** What are the limitations of the existing approaches?
RQ5: What are interesting areas for future research in the field?

RQ1 is motivated by the need to get insight in the research trends in self-adaptive systems, providing context for the study. RQ2 and RQ3 are the central research questions in this study. The goal of RQ4 and RQ5 is to help deriving conclusions from the study.

B. Quality Criteria

All studies are assessed through a quality check, which is an inherent part of a thorough literature study. Checking the quality of the studies is important for data synthesis and interpretation of results later on. To assess the quality, we collected a set of quality items as show on Table I. These items are based on the assess method for research studies proposed in [11]. From the answers, a quality assessment score (max 12) is calculated by summing up the scores for all the questions for a study (scores for the various options are given between brackets).

C. Data Items

For each study, the data items shown in Table II were collected. Six reviewers read each paper in detail and extracted the data in a form. This data was used during a discussion to resolve conflicts and reach consensus for the data items.

The data items author, year, title, and keywords (F1-F4) were used for documentation purposes. Citation count (F5) is the number of references provided by Google Scholar in December 2011. Quality score (F6) is the sum of the scores for the quality criteria described in section II-B.

Category of the study (F7) has the following options:
- theory (study of a new theory about any aspects of self-adaptation)
- engineering (study about any aspects of the development, operation, or maintenance of self-adaptive software systems)
- application (study about a particular application in which self-adaptation is applied)
- empirical study (systematical empirical inquiry, including case study, controlled laboratory experiment, and controlled experiment performed in industry setting)
- survey (study of a collection of data about any aspects of self-adaptation, typically, by reviewing literature in the field of self-adaptation)
- other.

Subject of the study (F8) refers to the general theme of the study. Options are:
- concepts (study about new ideas/abstractions of self-adaptation)
- models (study of a new model or models that describe any aspects of self-adaptation)
- behavior (study about any aspects of the behavior of self-adaptive systems)
- requirements

<table>
<thead>
<tr>
<th>Quality item</th>
<th>1. Problem definition of the study. Options are:</th>
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<tbody>
<tr>
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<td>(2) The authors provide an explicit problem description for the study.</td>
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<tr>
<td></td>
<td>(1) The authors provide a general problem description.</td>
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<tr>
<td></td>
<td>(0) There is no problem description.</td>
</tr>
<tr>
<td>2. Problem context of the study. Options are:</td>
<td>(1) If there is an explicit problem description for the study, this problem description is supported by references.</td>
</tr>
<tr>
<td></td>
<td>(0.5) If there is a general problem description, this problem description is supported by references.</td>
</tr>
<tr>
<td></td>
<td>(0) There is no description of the problem context of the study.</td>
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<tr>
<td>3. Environment in which the study was carried out. Options are:</td>
<td>(1) The authors provide an explicit description of the environment in which this research was performed (e.g., lab setting, as part of a project, in collaboration with industry, etc.).</td>
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<td>(0.5) The authors provide some general words about the environment in which this research was performed.</td>
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<td>(0) There is no description of the environment.</td>
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<tr>
<td>4. Research design of the study refers to the way the study was organized. Options are:</td>
<td>(2) The authors explicitly describe the plan (different steps, timing, etc.) they have used to perform the research, or the way the research was organized.</td>
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<td>(1) The authors provide some general words about the research plan or the way the research was organized.</td>
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<td>(0) There is no description of how the research was planned/organized.</td>
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<td>5. Contributions of the study refers to the study results. Options are:</td>
<td>(2) The authors explicitly list the contributions/results of the study.</td>
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<tr>
<td>6. Insights derived from the study. Options are:</td>
<td>(2) The authors explicitly list insights/lessons learned from the study.</td>
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<td>(1) The authors provide some general words about insights/lessons learned from the study.</td>
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<td>(0) There is no description of the insights derived from the study.</td>
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<td>7. Limitations of the study. Options are:</td>
<td>(2) The authors explicitly list the limitations/problems with the study.</td>
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<td>(1) The authors provide some general words about limitations/problems with the study.</td>
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<td>(0) There is no description of the limitations of the study.</td>
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- architecture
- framework (study about a software framework, i.e. software providing generic functionality that can be selectively changed or extended to provide application specific software)
- implementation
- testing
- verification
- other.

Concrete focus (F9) refers to the specific subject of the research. Options are:
- one or more of the activities of self-adaptation (i.e. monitoring of the managed system or the environment, analysis of the collected data, planning of adaptation, execution of adaptation)
Table II
DATA COLLECTION FORM

<table>
<thead>
<tr>
<th>Item ID</th>
<th>Field</th>
<th>Concern / research question</th>
</tr>
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<tbody>
<tr>
<td>F1</td>
<td>Author(s)</td>
<td>Documentation</td>
</tr>
<tr>
<td>F2</td>
<td>Year</td>
<td>Documentation</td>
</tr>
<tr>
<td>F3</td>
<td>Title</td>
<td>Documentation</td>
</tr>
<tr>
<td>F4</td>
<td>Keywords</td>
<td>Documentation</td>
</tr>
<tr>
<td>F5</td>
<td>Citation count</td>
<td>RQ3</td>
</tr>
<tr>
<td>F6</td>
<td>Quality Score</td>
<td>RQ3</td>
</tr>
<tr>
<td>F7</td>
<td>Category of the study</td>
<td>RQ1</td>
</tr>
<tr>
<td>F8</td>
<td>Subject of the study</td>
<td>RQ1</td>
</tr>
<tr>
<td>F9</td>
<td>Concrete focus of the study</td>
<td>RQ1</td>
</tr>
<tr>
<td>F10</td>
<td>Application domain</td>
<td>RQ1</td>
</tr>
<tr>
<td>F11</td>
<td>Disciplined split</td>
<td>RQ1</td>
</tr>
<tr>
<td>F12</td>
<td>Concerns</td>
<td>RQ2</td>
</tr>
<tr>
<td>F13</td>
<td>Claimed benefits</td>
<td>RQ2</td>
</tr>
<tr>
<td>F14</td>
<td>Tradeoffs</td>
<td>RQ2</td>
</tr>
<tr>
<td>F15</td>
<td>Assessment approach</td>
<td>RQ3</td>
</tr>
<tr>
<td>F16</td>
<td>Evidence level</td>
<td>RQ3</td>
</tr>
<tr>
<td>F17</td>
<td>Repeatability</td>
<td>RQ3</td>
</tr>
<tr>
<td>F18</td>
<td>Findings</td>
<td>RQ4</td>
</tr>
<tr>
<td>F19</td>
<td>Limitations</td>
<td>RQ4</td>
</tr>
<tr>
<td>F20</td>
<td>Challenges</td>
<td>RQ5</td>
</tr>
</tbody>
</table>

- runtime models to support adaptation (i.e., models that are reified at runtime to support self-adaption)
- reflection/meta-level computation (i.e., software that observes and modifies its own structure or behavior)
- multiple MAPE/control loops (including decentralization, coordination, etc.)
- other.

Applications domains (F10) for which self-adaption is used (in case the study is about a particular application) or applied for evaluation (in case the applications are used for illustration, evaluation, etc.). Possible application domains are: parallel computing (grid, parallel computing, cloud computing etc.), service-based systems (webservices, business applications, e-commerce, etc.), client-server systems, embedded systems, robotics, traffic and transportation, and other.

Disciplined split (F11) is one of:
- the managing system is clearly separated from the managed system; the latter comprises the application logic that provides the system’s domain functionality
- the managing system is clearly separated from the managed system; the latter comprises resources/hardware - resources can be CPU cycles, memory, bandwidth, etc.; hardware can be an engine, a cooling installation, etc.
- managing and managed system are mixed; the software of both systems is partially or completely interwoven
- not applicable.

Concerns of self-adaption (F12) refers to what is of interest and influenced by self-adaption (positively or negatively). Options are:

1. Quality concerns related to self-adaptation, i.e., quality attributes that are influenced by self-adaptation in the study. The options (based on IEEE 9126 and ISO/IEC 25012) are:
   - reliability (fault tolerance, recoverability): capability of software to maintain its level of performance under stated conditions for a stated period of time
   - availability: the degree to which the software is in a functioning condition, i.e. capable to perform its intended functions
   - usability (ease of learning, communicativeness): effort needed to use the system
   - efficiency/performance (time behavior, resource utilization): efficiency of the software by using the appropriate resources under stated conditions and in a specific context of use
   - maintainability (analyzability, changeability, stability, testability): effort needed to make specified modifications.
   - portability: ability of software to be transferred from one environment to another
   - security: ability of the system to protect against misuse
   - accuracy: the extent to which the software realizes the intended behavior in a specific context of use
   - flexibility in use: capability of the software to provide quality in the widest range of contexts of use, incl. dealing with unanticipated change and uncertainty
   - other.

2. Other concerns related to self-adaptation, i.e., any other concerns that are influenced by self-adaptation in the study. Examples are quality of the engineering artifacts, costs, benefits, etc.

Claimed benefits of self-adaptation (F13) can be one or more of the following (refers to concerns selected in F12):
- preserving quality of the software (i.e., quality attributes that are maintained by self-adaptation)
- improving quality of the software (i.e., quality attributes that are improved or added to the system by self-adaptation)
- assuring quality of the software (i.e., quality attributes that are guaranteed by self-adaptation, typically supported by strong evidence or formal proof)
- other concerns that are positively influenced by self-adaptation.

Tradeoffs (F14) refers to the concerns of self-adaptation with a negative impact (as selected in F12). This can be one or more of the following:
- quality concerns that are negatively influenced by self-adaptation
- other concerns that are negatively influenced by self-adaptation.

Assessment/validation (F15) has the following options:
- discussion (a qualitative, textual, opinion-oriented evaluation; e.g., comparison, oral discussion of advantages
and disadvantages; the discussion may include the
description of examples that may not have been realized)

- example application (assessment based on a concrete
  application or applications; the example application
  is concretely realized, but not necessarily completely
described in the study)

- simulation (execution of a system with artificial data
  using a model of the real world; includes typically
  a comparison of the proposed approach with a baseline/benchmark)

- rigorous analysis (rigorous derivation and proof; rigor-
  ous analysis is typically based on formal methods)

- empirical study (systematical empirical inquiry to pro-
  vide evidence for or against any particular theory
  or hypothesis by means of accurate analysis of data
  obtained from observation or experience)

- experience from real examples (the results have been
  used on real-world examples, but not in the form of
  empirical studies; the evidence of its use is collected
  informally or formally)

- none

Evidence level (F16) is one of the following options:

- no evidence
- evidence obtained from demonstration or application to
  simple/toy examples
- evidence obtained from expert opinions or observations
- evidence obtained from empirical studies
- industrial evidence
- other

Repeatability (F17) has the following options:

- study is not repeatable (no useful description of mate-
  rial is available to repeat the study)
- a partial description is available to repeat the study
  (may be described in the paper)
- the material to repeat the study is partially available
  (this typically includes links to material that can be
  used to repeat the study)
- all the material is available to repeat the study (the
  study can be repeated with reasonable effort, probably
  in a different but similar setting)
- other.

F18, F19, and F20 refer to the study as a whole. Findings
(F18) briefly lists (i) the stated contributions of the study,
and (ii) the stated insights/lessons learned derived from the
study. Limitations (F19) enumerates the stated shortcomings
or problems with the study, and Challenges (F20) lists open
problems identified by the authors for future research.

D. Data Analysis

The data derived from the the studies was collated and
summarized to answer the research questions. The synthesis
included the following:

1) listing of findings,

2) reaching consensus among reviewers in case of con-
flicting opinions,

3) analysis of findings,

4) answering research questions and interpretation of the
results.

Based on the synthesis, we derived conclusions and rec-
ommendations for future research in the field. Finally, we
reflected on the validity of the review.

III. RESULTS

We now discuss the study results based on the research
questions we defined for the study.

RQ1: What is the focus of research in self-adaptive systems?

Research focus is derived from the following concerns:
category of the study (F7), subject (F8), concrete focus (F9),
application domain (F10), and disciplined split (F11).

Overall, from the 124 studies, 90 studies focused on
engineering and 6 studies on applications. Only these 96
studies, which make up 77 % of the total number of papers,
were considered in the rest of the review. The remaining
papers are theory studies (12), surveys (5), roadmap papers
(2), and short papers (10).

Figure 2 shows the frequency of the subjects of the
studies. Not surprisingly, architecture (26 %) together with
models (24 %) account for half of the studies, as the roots
of the field lay in architecture and runtime architectural
models. Note that the specific attention for architecture has
significantly decreased after 2008, while the inverse effect
can be noticed for models. We also notice that there is little
interest in formal verification since 2008, while there is a
growing interest in frameworks, requirements, and testing.

![Figure 2. Subjects of the studies (number of studies).](image_url)

Figure 3 zooms in on the concrete focus of the studies. 56 % of the studies focus on one or more activities of self-
adaptation (monitoring, analyzing, planning, execution), and 18% focus on runtime models. We notice a spectacular increase of interest in runtime models after 2008 (factor of 8); the connection with the organization of the models@runtime workshop seems evident. 10% of the studies focus on multiple control loops, and 4% focus on reflection.

Figure 3. Concrete focus of the studies (number of studies).

Figure 4 shows the data extracted from the application domains for which self-adaptation has been used (F10). Our particular interest was in coarse grained families of systems. Service-based systems account for 34% of the applications, and this portion is increasing. Dynamic service composition is a very active area for self-adaptation. Robotics, which has always been an important domain in self-adaptation research, accounts for 15%.

We also looked at the separation of concerns between managed and managing system. The data extracted from disciplined split (F11) shows that 70% of the studies make a strict separation between the managed system and the managing system. 56% of the studies consider managed systems comprising of software, the remaining 14% consider managed systems comprising of resources or hardware. In 30% of the studies, the managed system and the managing system are interwoven. Whereas a strict separation of concerns may indicate disciplined engineering practice, a number of authors deviate from this principle due to the invasive nature of particular types of self-adaptation, and the use of self-organizing, agent-based approaches.

RQ2: What are the claimed benefits of self-adaptation and what are the tradeoffs implied by self-adaptation?

To answer this question, we used data extracted from concerns (F12), claimed benefits (F13), and tradeoffs (F14). We assessed all the concerns that are of interest for self-adaptation in the studies. Overall, we found that 94% of the concerns were quality attributes. Top quality attributes are flexibility (31%), reliability (29%), and efficiency/performance (27%). Particularly underrepresented are availability, accuracy, usability, and security that all together make up only 12% of the reported concerns. The remaining 6% other reported concerns include complexity, engineering effort, and budget.

Figure 5 summarizes the claims versus the tradeoffs of self-adaptation. The figure clearly demonstrates that the papers mainly report on claimed benefits, while little attention is given to the implications of self-adaptation. 39% of the studies considered a single concern, 47% considered 2 concerns, the remaining 14% considered 3 or 4 concerns. 85% of the considered quality attributes are claimed to be positively influenced by self-adaptation and the remaining 15% are negatively influenced. It is remarkable that efficiency/performance is almost the only reported quality attribute with a negative effect as a result of self-adaptation (besides a few studies that report a negative impact on availability and accuracy). We also assessed the type of claims that were made for the quality attributes and found that the dominant claim is improvement of software quality attributes (88%). The remaining 12% is equally distributed over preserving and assuring quality attributes. Note that the ratio claims versus tradeoffs for the other concerns show an inverse image as for the quality attributes, i.e., 70% of the other concerns are negatively affected and 30% positively.

RQ3: What assessment methods have been used and how much evidence is available?

To answer this question, we drew on data extracted from citation count (F5), quality scores (F6), assessment approach (F15), evidence level (F16), and repeatability (F17). Citation counts shows an average of 16 citations for SEAMS papers from 2006 and 2008, and an average of 8 citations for 2007, 2009, and 2010. The SeFSAS book has 4 papers with +30 citations. As it is well-known that it is difficult to derive conclusions from the number of citations
more attention when reporting on research results of self-adaptation. Note that the average of the total quality scores is 5.40 out of the maximum total of 12, which means that on average in terms of quality the studies are neither perfect, nor are they completely flawed. Table III shows the studies with a quality score of plus 8.

Figure 7 shows the assessment methods used in the studies. Example application and discussion make up 90% of the used assessments. Only a few (quasi) empirical studies and no assessment on real applications are reported.

4The total quality score of a study is the sum of the quality scores for all the quality items, as described in Table I.
5With empirical studies we refer to systematic investigations, including surveys (investigation of a topic based on data derived from interviews or questionnaires from a representative sample of the target population), case studies (investigation of a topic by observational investigation and statistical analysis of collected data), and experiments (a rigorous and controlled investigation in which subjects are assigned to different treatments at random and the effects are determined based on statistical analysis of collected data).
RQ4: What are limitations of the existing approaches?

Research limitations are derived from the data items: findings (F18), and limitations (F19). We identified the following recurring themes in the reported findings:

- **Technology**: existing technology can be exploited to support self-adaptation, e.g., aspects, reflection, standard interfaces (15 studies)
- **Complexity**: realizing self-adaptation is complex, e.g., implementing control loops, goal models, debugging, etc. (5 studies)
- **Model vs. Implementation**: building a solution may reveal a mismatch between the architectural models and the actual implementation (5 studies)
- **Invisiveness**: the managed system needs to be build/prepared to support self-adaptation (3 studies)

Themes identified in the reported limitations are:

- **Domain-specific solutions**: solutions that are only applicable to a given domain/application (13 studies)
- **Simplifying Assumptions**: simplifications of the system or software on which the approach relies on (11 studies)
- **Performance**: the overhead of the adaptations, inefficiency of the decision making, etc. (7 studies)
- **Manual effort**: the amount of manual effort and cost required for using the approach (4 studies)
- **Evaluation**: the lack of sufficient evidence that the approach really works (3 studies)
- **Accuracy**: the lack of adequate accuracy of the approach in achieving the objectives (2 studies)
- **Guarantees**: the absence of proofs or guarantees about reliability, safety, etc. (2 studies)

These themes confirm several limitations we derived from earlier analysis, including simplifying assumptions and limited assessment. It is important to note that the majority of the studies (66%) report no limitations.

RQ5: What are interesting areas for future research?

Areas for future research are derived from data item challenges (F20). We identified the following themes in the collected data:

- **Improve experiments/evaluation**: proper evaluation and experimentation of a research was difficult and could be improved (52 studies)
- **Enhance technique/theory**: the authors identify a challenge or the need for enhancing the foundations of the approach/research (52 studies)
- **Develop tool support**: development of tool support is necessary for the approach to be practical for use (25 studies)
- **Formalize and refine concepts**: there is a need for better describing or rigorously specifying concepts, techniques, languages, etc. (23 studies)
- **Revisit assumptions**: some of the assumptions were oversimplifying and need to be revisited in the future (19 studies)
A. Limitations of the Study

One threat to internal validity with the study is the involvement of students as reviewers, which may compromise the relevance of the results. We have anticipated this issue by paring two groups of students with two established researchers in the field to evaluate each study. During the interactive discussion sessions, we noticed that the students progressively improved their evaluation skills. In the second half of the review process, a majority of the students showed advanced competence in performing reviews.

Another threat to internal validity is the existence of bias of the reviewers. To reduce bias, we have opted to let 6 reviewers perform the initial reviews of each paper independently. Then the results were compared and discussed in case of conflicts. Bias in the design of the study and the analysis of results was kept low by involving four researchers, of which two effectively performed the reviews, the other two researchers provided feedback and supported analysis.

As we have only looked at studies of SEAMS, there is a threat to external validity with respect to the generalization of the conclusions of the study. In particular, as SEAMS was a workshop until 2010, this may explain the lack of thorough evaluation of many studies. In this respect, we do not make any claims concerning the results for the whole field. Nevertheless, as we studied a significant part of the literature on self-adaptive systems, the results are definitively valid, though not conclusive. Therefore, a complete systematic review [8] is needed, an effort we plan to start in the near future.

B. Related Work

We limit the discussion to a number of recognized papers in the field that discuss related aspects, and an interesting survey paper that was recently presented at SEAMS.

C. Recommendations

Based on the insights derived from our study, we offer the following recommendations to move our field forward:
To be able to evaluate better, we need the community to make their methods, tools, and data available, and even better use a couple of studies as examples, Znn.com\(^6\) is one excellent candidate.

To address the limitation and assumption issues, conferences/workshops in this field should require a limitation and assumption section for every paper, very similar to how the empirical software engineering papers are expected to have by default a threats to validity section.

To address the weak treatment of tradeoffs implied by self-adaptation, a discussion of tradeoffs should be an explicit aspect of reviews, and finally

To stimulate academy-industry collaborations, such efforts could be given special recognition at conferences, e.g., by awarding the best studies, similar as the SPL community (splc.net/fame.html). Such recognition could feed discussions about what constitutes excellence and success in self-adaptation.

V. CONCLUSIONS

The objective of this literature study was to summarize existing research on engineering self-adaptive software systems and shed light on the claimed benefits and provided evidence of self-adaptation. The study shows that researchers clearly explain problem and contributions of their studies, but the description of the research design and limitations can be improved. The main focus of the research is on architecture and models, with particular attention on the activities of self-adaptation and runtime models. The dominant application domain for applying and evaluating self-adaptation research is service-based systems, followed by robotics. The primary claims of self-adaptation are improved flexibility, reliability, and performance of the system. The main reported tradeoff implied by self-adaptation is performance overhead, but tradeoffs have not received sufficient attention. Evidence is often obtained from applying the research to simple examples. Only a few systematic empirical studies have been undertaken, and no industrial evidence is reported. Some areas that deserve further research are requirements, verification, testing, multiple control loops, and the application of self-adaptation for other quality attributes, such as usability and security. From our study, we derived the following recommendations to move the field forward: researchers should make their assessment methods, tools and data publicly available; conferences/workshops should require an explicit section on limitations in engineering papers; discussion of tradeoffs should be an explicit aspect of reviews; and successful academy-industry collaborations could be formally recognized by the community.

Over the past 20 years, several researchers in the wider software engineering community have repeated the need for systematic evaluation [15]. This systematic study confirms that this observation also applies to the SEAMS community. We hope that the results of this study and the proposed recommendations can be useful for our community as a step towards improvement of the research in our field.

REFERENCES


