Spiral Approach for SE Research (SASER) – mating research to practice –

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Abstract

Systems Engineering research findings often fail to be adopted by industry, despite using a thorough and rigorous research methodology like the Design Research Methodology (DRM). Industry as Laboratory is a research approach that improves relevance for industry by embedding parts of the research in real industry settings. A drawback is that experimenting in industry is done after extensive and time consuming analysis, leading to lost interest by the company. Further the extensive analysis phase described in the DRM can result in *analysis lock-in* for the researcher. The Spiral Approach for Systems Engineering Research (SASER) introduced here increases the rate of experimenting in industry by mating the established spiral development approach with rigorous design research as defined in the DRM. This way, the company can see and adopt findings earlier, and the researcher can see the results sooner. The expectation is that not only the company remains interested, but also the researcher stays motivated and avoids the analysis lock-in. The paper presents SASER and illustrates it with a descriptive example.

Keywords: Systems Engineering Research, Spiral Development, Research Methodology

1 Introduction

Systems Engineering (SE) research is challenging (Muller, 2005a,b). It is a form of Design Research (Eckert et al, 2003), where the thorough and rigorous Design Research Methodology (Blessing and Chakrabarti, 2009) and Wieringa's Design Science Methodology (Wieringa, 2014) are useful. However, while most of the SE findings from research are not complex, showing their value in real development situations, verifying and validating the research, is difficult for a number of reasons. These include the limited time and resources for research where real SE projects take years and hundreds or thousands of man-years, and the time delay between SE introduction and harvesting its benefits. Another reason is the infeasibility of doing parallel comparative research combined with the invalidity of sequential comparative research. Finally, there are issues related to matching industry needs with academic requirements and scalability issues, resulting in limited adoption of academic findings. For these reasons, successful SE research includes application to real life situations (Crawley, 2021), and is modest in its claims (Muller, 2012, 2013).

Industry as Laboratory (IaL) is a way for SE research (Potts, 1993; Muller, 2013) to deal with the issues above. Here, an SE approach or method under development is tried out in industry, often by the researcher him-/herself. This form of *Action Research* has helped in, amongst others, showing the value of the A3 Architecture Overviews (as we will see in Sec. 3).

Close contact with a company is essential for successful implementation of IaL. It often takes years of trust building before a company allows researchers to look in the kitchen. If trust is there, it is essential to keep and cherish it. Losing it by keeping the company waiting (too) long for useful results is a risk.

Although the idea of using a spiral approach for research is not new (Eckert et al, 2003; Bodner et al, 1999), yet to the best of the authors knowledge no recent follow up studies further developed the idea of agile research through a spiral approach. Our paper innovates by presenting a practical approach to organizing the research questions into a spiral, thereby mitigating the previously discussed issues. We propose, in line with existing research and development approaches, a Spiral Approach to SE Research: SASER.

Structure of the paper

In the next Section we discuss design research, looking at general and Systems Engineering specific aspects. Section 3 deals with Industry as Laboratory. After shifting focus briefly to SE development methods (Section 4), we introduce a spiral model for SE related research in Section 5. Section 6 presents an example of how it can be applied. We end the paper with a discussion, and conclusions, recommendations and future work in Sections 7 and 8, respectively.

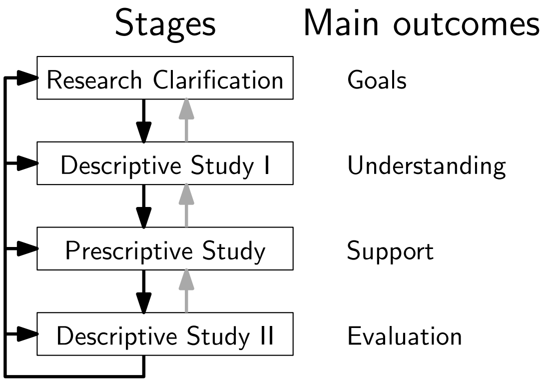

Fig. 1 The Design Research Methodology (DRM) as introduced in (Blessing and Chakrabarti, 2009)

2 Research background

A host of research methods exist. Depending on whether the issue at hand is of applied or fundamental nature, whether we are exploring or aiming at conclusive results, specific approaches are applicable.

As soon as we talk about SE research, we need to take aspects from design research into account: by creating a design once, we have increased the knowledge level of the people involved. Simply retrying the design again invalidates comparison. References (Eckert et al, 2003; Birkhofer, 2011; Andreasen, 2011) give an overview of development of design research over several decades.

In the next subsections, we will look at general design research and specific SE design research.

2.1 General design research

The Design Research Methodology (DRM) by Blessing and Chakrabarti (Blessing and Chakrabarti, 2009) is a well-structured and comprehensive research methodology, that addresses research in the field of design. It provides a framework for many types of design researches, both explorative and conclusive. The methodology facilitates rigour in the design research field.

The DRM framework consists of four stages, see Fig. 1:

1. Research Clarification: literature analysis to describe the research goals.
2. Descriptive Study I: empirical study of the current state of the problem, leading to understanding.
3. Prescriptive Study: facilitate development and application of design support (in the widest sense) and
4. Descriptive Study II: evaluate the impact of the developed support.

Wieringa's Design Science Methodology (DSM) (Wieringa, 2014) originates from the information systems and software engineering field, yet it is more broadly applicable and can serve as a framework for design research. The strength of DSM is that it matches research practice to design practice. DSM recognizes the differences between answering knowledge questions (= research) and designing (= creating) an artefact that is meant to improve a situation. As such, there is a relation to design approaches like Rapid Knowledge Cycles and Knowledge Based Design. Crucial in the DRM and DSM is the formulation and subsequent answering of *Research Questions* (RQs). In DSM these are differentiated in knowledge and design questions.

References (Eckert et al, 2003; Wieringa, 2014; Blessing and Chakrabarti, 2009; Birkhofer, 2011; Andreasen, 2011), including references these contain, provide a multitude of ideas and views on design science methods; too many to summarize in the present paper. What can be concluded from them, is that while there is a long history of design science, the DRM and DSM appear to be the most comprehensive methodologies.

2.2 SE-specific design research

From (Martin and Davidz, 2007; Muller, 2013, 2009) and our own research experience, we can list particular issues related to SE research, expanding on the ones mentioned in the Introduction:

1. In a typical research project, there is only time and resources available to do an example or small-scale application.
2. No company is willing to have two parallel development teams, one using a new SE approach, the other one without it, so that a comparison could be made between the two approaches.
3. Sequential testing by trying development first without, and then with a new SE approach yields invalid results: as soon as the development is done once, information is available that was unavailable the first time. Reversing the two does not help in this respect.
4. While SE research is published in good academic papers, the methods and tools are not adopted in industry for various reasons like lack of visibility, mental inertia in developers, and difficulty to convince management.
5. Some SE academic results do not scale to real life situations.
6. It is hard to match the specificity and/or genericness of the research findings with industrial settings.
7. The overall value of SE is mostly only perceived after considerable time has passed since its introduction.

In this setting, many SE researchers resort to examples and lab-scale experiments to illustrate the usefulness of their developed systems design support, but lacking real-life evidence for real applications like development of a fighter jet or a wafer scanner.

Of particular importance is our observation that when researchers (in particular junior researchers in Master and PhD thesis projects), start with an elaborate problem analysis and literature search, tend to get absorbed by *gathering* information. In the type of research projects that are the focus of the present paper, there is no clear stop criteria for this analysis phase. Even worse, as Aristotle said "The more you know, the more you know you don't know."

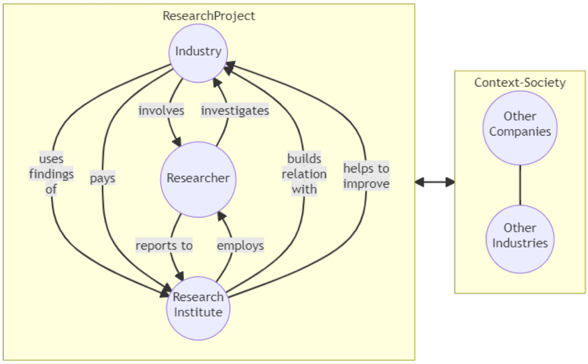

Fig. 2 Representation of relations in Industry as Laboratory research.

This leads to more and more analysis and literature searches, and a bigger barrier to start creating the intended systems engineering support. We call this *analysis lock-in.*

3 Industry as laboratory

A few practically applied systems engineering research projects include the earlier mentioned A3 Architecture Overviews (Borches Juzgado, 2010; Hooft et al, 2020; Wiulsrød et al, 2011), lean product development (Pessôa et al, 2012; Pessôa and Trabasso, 2017), FunKey architecting (Bonnema, 2008, 2011), Customer objectives, Application, Functional, Conceptual and Realization model (CAFCR) (Muller, 2004), and budget based design (Freriks et al, 2006; Frericks et al, 2006). Reference (Falk and Muller, 2019) provides a high-level overview of research involving master students. Common element is the use of the Industry as Laboratory approach.

Industry as Laboratory is a form of Action Research using industry practice to find and formulate problems or issues that require solution or improvement (Potts, 1993; Muller, 2013). Also, industry practice is used for evaluating the effectiveness of developed approaches and methods. There is a strong parallel with conventional (chemistry or physics) laboratories in facilitating experimenting to gain understanding, and try out solutions and approaches. Note that it is essential to have safety measures in place in both. The safety goggles and lab coats in conventional labs find their parallels in IaL in ethical reviews on the research method, data security and confidentiality agreements.

An important difference from a conventional lab relates to ownership: where a conventional lab is generally owned by the scientific institute, in IaL the industry "lab" is owned by completely different (private) entities. Much like it is not allowed for a complete stranger to start experimenting in a conventional lab, a SE researcher cannot just enter a company to use it as laboratory. It requires considerable effort and time to create the essential trust between research institution and industry before actual experiments can start. A particular interest in running an IaL research project or program is therefore tending to the relationships between Industry, Research Institute and Researcher, see Fig. 2. Note that the Industry, the Research Institute and the Researcher also have relations to other stakeholders not shown in the picture.

Nurturing the relationships requires special attention to the interests of the industry since they are often funding a significant part of the project in addition to existing subsidies. Of particular interest is the attention that has to be paid to the results and findings over the course of the project. This is overseeable in the short (6 months) master projects discussed in (Falk and Muller, 2019), but becomes a challenge in typical PhD projects of four years.

4 SE development methods

The traditional systems engineering approach is the waterfall, guaranteeing rigour but limiting concurrency. The Vee-model is nowadays considered common practice in SE. Where one should interpret the Vee-model as a reference model, showing the relations between development and verification/validation activities. This way, one can see also concurrency.

There is a strong pressure to combine SE with *Agile* development practices (Douglass, 2016; Dove and Labarge, 2014 (updated 2018). The spiral development originally proposed for software engineering (Boehm, 1988) is a widely adopted approach in this respect. This led us to present in (Bonnema et al, 2016), a generic picture for spiral development, see Fig 3. Summarizing, the approach is to *observe* practice, *abstract* the findings to generalize and allow for use in future and possibly (somewhat) different contexts, *create* a product or system to reduce or eliminate the observed problem, and then *implement* the product or system in real life. From then, the cycle recurs with *observing* the changes. This spiral is intended for developing complex products and systems. Every loop in the spiral results in more knowledge and understanding of both the problem and the solution, and at the same time showing progress to different stakeholders. The general outward progress shows that the developed system becomes more comprehensive in each loop. The model can even resemble subsequent development of new product versions in every loop.

As we will see in the next section, we propose this cycle also to SE research projects while keeping connection to the structured DRM and DSM research approaches.

5 Mating SE research to SE development

Both the DRM and DSM provide a rigorous structure to come to research that results in a coherent and valid report or thesis, in much the same way as a *waterfall* development process results in solid results, but in a slow way. To ensure rigour, we reuse from the DRM the way that Research Questions are formulated in the Spiral Approach for Systems Engineering Research (SASER). SASER differentiates in the way that answers are developed.

Building upon concepts introduced in (Eckert et al, 2003), in line with the DRM (and DSM), the first phase in SASER is the *Research Clarification*. Based

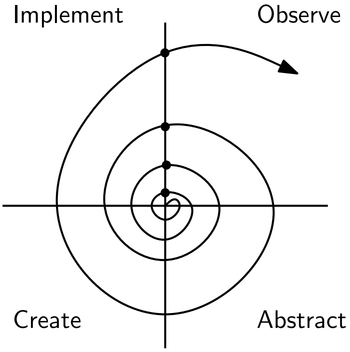

Fig. 3 Representation of a generic spiral development approach, inspired by (Boehm, 1988) and the Deming cycle.

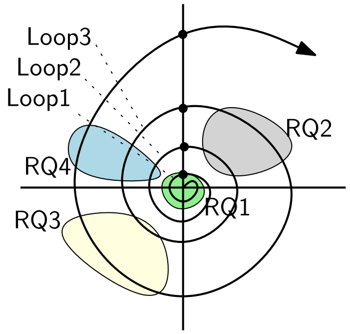

Fig. 4 Visualization of SASER, showing the loops and possible locations of different Research Questions (RQs).

on initial observations, a scan of literature (Axelsson, 2015) and overview of the state of the art and practice[1], a research plan including focus, goals and main research questions (RQs) is formulated.

Next step is to plan the loops in the Spiral approach. Here, the following should be considered:

1. Where is the value for the industry involved?
2. Can partial answers to a RQ be used to start answering a next RQ?
3. What preliminary results or concepts can be defined?
4. How can preliminary results or concepts show value to the company?
5. What are ways of evaluating the preliminary results or concepts.

Based on those, one can identify ways for answering the RQs; we will denote those as δRQs. So, for RQ3, for example four answer means can be defined: $\delta RQ3^a$ through $\delta RQ3^d$. Partial answers and concepts can take the form of, for instance, concept presentation, mock-ups, *wizard of Oz* prototypes and small scale implementations. To elaborate on the loops, map the loops like the one in Fig.4 or Fig. 5. Final part of planning a SASER project is to schedule the loops in time, e.g. define 6 months for Loop 1, 8 for Loops 2 and 3 each, etc.

We expect the following benefits based on preliminary experiences:

- Better interaction between research and application;
- Reduced barrier between analysis and creation;
- Increased motivation for the researcher(s):
  - the feedback latency is significantly reduced, and
  - results can be seen in practice instead of only in theory;
- Better involvement of the industry:
  - more control over the course of the research;
  - earlier results that may already be useful;
- For research projects involving multiple researchers and/or companies, the earlier loops provide a means to explore collaboration settings.
- Research results at a higher TRL by the end of the research project.

[1] State of practice is a rich source of information in SE research.

- Easier to define future research by extrapolating the loops.

Based on our preliminary findings, we can also identify drawbacks:

- More complex planning process, resulting in more time and effort required for planning;
- Additional trade-offs to be made between defining intermediate findings and their reliability for the subsequent research steps;
- Danger of too much focus on the intermediate results so that the end goal moves out of sight; potentially leading to misalignment between goal and intermediate results.

Reporting on the findings in actual research projects is future work.

6 Example of spiral SE research

To illustrate SASER, this Section will provide an example. While not an actual project, it is heavily inspired by research projects in our group, where the SASER approach is already being implemented. These real projects have been running for 7-14 months at the time of writing. Also, one older project that has undergone delays (a.o. due to the pandemic) is being restarted using SASER. We plan to report on these projects when results are obtained in the future.

Company X is struggling with making decisions in their Systems Engineering approach. The company has developed from a start-up to a respected equipment manufacturer in the semiconductor industry over the past decade. Their speciality is in peripheral equipment needed in chip manufacturing. The company has now about 100 employees in development, of which about ten persons have systems engineering responsibilities. Six of these ten people are new in the company because of strong growth, and they have limited SE experience. Hence the DRUM (Decisions in Regular and Unplanned Module development) Industry as Laboratory project is initiated by Company X and the University in the region. Main objective is to develop decision support in the field of high tech equipment development.

Based on a research clarification (DRM) of two months, the following research questions are formulated:

RQ1 What is the state of the art and practice in Decision Support (DS)?
RQ2 Where are decisions made in Company X that require better support?
RQ3 What forms of DS is applicable in the decisions found in RQ2
RQ4 How would a DS system for Company X look?
RQ5 What is the added value of using the developend DS in Company X and in general?

RQ1 relates to the DRM Research Clarification, RQ2 to the Descriptive Study I; delineating the project's context, RQ3 and RQ4 to the Prescriptive Study; and RQ4 also shows the design side of the project, and finally RQ5 relates to the Descriptive Study II (see Fig. 1). These RQs are still on a high level. Some of the more detailed steps to answering the RQs are formulated as δRQs:

δRQ1 a Literature search and mapping
b State of the practice in Company X

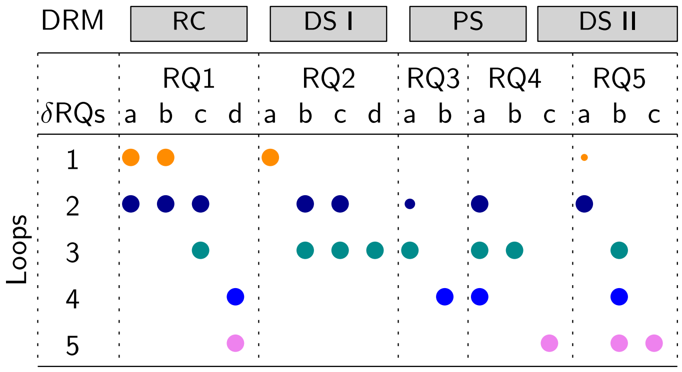

Fig. 5 Mapping the answer stages to research loops in the DRUM project with Company X. The top row indicates the DRM stages. Dot diameter represents relative impact.

- c State of the practice in the field.
- d Current developments in ongoing research.

δRQ2
- a How are decisions being made in Department A,B,C
- b How is decision making perceived in Department A,B,C
- c Good decision making examples
- d Bad decision making examples.

δRQ3
- a Prioritising issues
- b Mapping DS approaches to Company X.

δRQ4
- a Mock-up
- b Prototype with limited functionality
- c First version.

δRQ5
- a How to measure decision quality?
- b How does the support improve decisions in Company X?
- c How does the support improve decisions in another company/other companies?

One should extend, and possibly expand, this list. However, we leave that out for the sake of brevity of the example in this paper. The subsequent mapping of the δRQs to the loops is shown in Fig. 5.

The loops have relevance for research, as clearly follows from Fig. 5. For Company X, the relevance is already shown in Loop 2, where a mock-up is planned. Also, $\delta RQ2^a$ and ^{b} give valuable feedback to the company in Loops 1, 2 and 3. Thus, already after about one year, Company X can try out and experiment with the developing DS.

7 Discussion

As stated, there is not yet a completed project that used SASER, but several projects are now embracing this approach. In one case, the PhD student suffered from analysis lock-in, and is now benefiting from SASER. We will further report in the future on how SASER has helped or hindered Industry as Laboratory projects. Revisiting the 7+1 issues of Sec. 2.2 and our expectations in Sec. 5, we can see how SASER is envisioned to help.

By starting earlier with showing value of the development support in a given research project, the researcher is enabled to work on larger application projects. Still, the time available is insufficient to validate in a full-blown, real-life case.

Comparison between new approaches and the currently implemented processes is facilitated by creating multiple loops, most of them with their own application part. One of the earlier loops shall incorporate an observational application, where no support is employed, but the researcher inventories the existing process and tooling in the company (DRM's DSI). This is a very useful aspect, as it helps in creating understanding of the company involved by the researcher. Also, as reported by a company in a starting SASER project, early loops help in testing the waters and preparing the company to act as experimentation environment. The sequence of loops, with ripening support over time, automatically creates triangulated results (meaning the incorporation of multiple ways of application: if they point in the same direction, the claims of the research can be trusted more than when only one example or a small application is shown.). Along the course of the project, the loops directly show the company how to employ the developing support. This makes implementing it in everyday use easier. Even more so, employees of the company can already use the support when they have been involved in the research project, even without being explicitly instructed.

SASER does not directly affect the scaling, and specificity and genericness issues. However, by making sure the researcher is well aware of the company's operations and the nature of the problems perceived by the company, scalability and applicability of an SE support will be much more tangible, and therefore improvements in these respects shall follow. SASER will take the value for the company into account in the loops, so that it already becomes apparent over the course of the research project.

The potentially largest contribution we foresee – and we already observe it in the ongoing projects – is avoiding the analysis *lock-in* that researchers often experience when they analyse state of the art and the practice based on literature and company's processes. By having more frequent shorter analysis phases that are intertwined with creative and application phases, the mechanism that creates *analysis lock-in* will be significantly less prominent.

8 Conclusions, recommendations & future work

Traditional waterfall type development projects in SE are highly goal oriented, and the results are in general of high quality. A drawback is the slow pace. In the same way, the DRM and DSM result in thorough, well founded research outcomes. But visible, let alone tangible, progress during the research projects may be slow.

Industry as Laboratory (IaL) facilitates research in systems engineering by providing a real life setting. IaL is a strong concept for Systems Engineering research as it enables experimenting on complex developments. For successful IaL research, the company involved must be kept interested.

The waterfall is in many development projects superseded by more agile approaches like spiral development. Design research has not yet followed the same trend. Research results may, as a consequence, become available only at a late stage of the research project, resulting in companies loosing interest.

In this paper we introduce the Spiral Approach to Systems Engineering Research (SASER) to increase agility and reduce long lead times for research outcomes, while maintaining rigour and solidity of the findings.

SASER puts emphasis on creating value for the company early by defining loops that touch several stages in the DRM and DSM. Each loop is intended to create value and show relevance to the company, and the sequence of loops results in full answering of the research questions. As a loop takes shorter time than a full research project, results become available at a higher rate than in purely DRM or DSM based research projects. In addition to creating value for the company at a faster pace, the researcher is expected to stay motivated by the intermediate results, and the reactions from the company. Also, SASER reduces analysis lock-in: the gap experienced by the researcher between analysis mode versus creation mode.

In the end, we expect a positive contribution to a society that struggles with ever more complex (design) questions.

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