Application and Validation of Systems Engineering Methods and Techniques in Practice

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ABSTRACT

The Systems Engineering Body of Knowledge (SEBoK) is often described as a set of best practices. However, literature provides little substantiation for applicability and value of the captured methods and techniques. A research question is when these methods and techniques are applicable, and how much they improve performance of project teams. Research challenges are to collect data in the real world - where most influencing factors are not under control of the researchers- and to cope with the heterogeneity of the field of application. For example, the system-of-interest can be an integrated circuit or a space station; it can be well bounded or embedded in a complex socio-technical environment.

This chapter reports our research in an industrial cluster, where we have sampled the application of various systems engineering methods and techniques in a variety of domains. We discuss the research methodology, and we show a number of emerging trends after taking 67 samples in industrial practice in Kongsberg. Examples of applied methods and techniques are requirements management, interface management, modeling, concept selection, and A3 architecture overviews and reports.

The amount of samples is too low to answer the main research question. We observed that application of methods and techniques from the body of knowledge is far from trivial. Current practice and culture in the organization constrain application of methods and techniques. In many cases, there is a clear potential for improvement. The researchers selected methods or techniques for application based on observed problems in the past. The evaluation often shows interest and a certain enthusiasm from the stakeholders for these methods and techniques. However, this enthusiasm in itself is insufficient to trigger changes; more pulling force is required to introduce these techniques at a broader scale.

INTRODUCTION

Researching Systems Engineering

The Systems Engineering Body of Knowledge (SEBoK)[1] is often described as a set of best practices. However, literature provides little substantiation for applicability and value of these practices. Best practices are often captured as methods and techniques. Our research question is when these methods and techniques are applicable, and how much they improve performance of project teams.

The Status of Systems Engineering as Discipline

Systems Engineering is a young discipline that is mostly practiced “in the field”, e.g. in industrial companies. Dixit and Valerdi [2] state that many systems engineers do their work based on experience.

An experienced group of INCOSE editors filled the Systems Engineering Body of Knowledge (SEBoK) [3] with a rich collection of best practices. Boehm, Valerdi, and Honour [4] research a hot question in the systems engineering community: what is the return on investment of applying systems engineering or what is the value of applying systems engineering. More general the academic question is "how do we know the effectiveness of these best practices?" More specific we like to be able to relate effectiveness to the context; what practice is appropriate in what circumstances?

Challenges of Researching Systems Engineering

Research challenges are to collect data in the real world -where most influencing factors are not under control of the researchers- and to cope with the heterogeneity of the field of application. For example, the system-of-interest can be an integrated circuit or a space station; it can be well bounded or embedded in a complex socio-technical environment. Additional challenge is that every experiment is unique; repeating an experiment with different parameters in the same setting is not possible.

In this chapter, we report the results of field research to study effectiveness of systems engineering methods and techniques in practice. Field research facilitates researchers to observe effectiveness when practiced in the field. Dominant research approaches to study in the field are action research [5] and industry-as-laboratory [6,7]. The researcher combines active participation in the systems engineering activities with the researcher role. The researcher is wearing two hats in these research approaches: as systems engineer and as researcher. The attitude of the systems engineer is result oriented and cooperative. The attitude of the researcher is questioning and challenging. Where the systems engineer will promote the use of a proposed method or technique, the researcher needs to question its validity.

Researchers in systems engineering are typically educated in the technical domain. However, effectiveness of systems engineering depends largely on human aspects, such as competence and behavior of individual stakeholders, social interaction between stakeholders, political circumstances, organization and governance, and many more. Research in systems engineering has to build on available scientific methods, both technical, as well as from the social sciences. Bhattacherjee wrote a good introduction in social science research [8].

Researchers can use a collection of case studies to evaluate theories or to form theories. However, the reverse approach, starting with case studies and eliciting theories is possible too. In the social sciences, Glaser and Strauss [9] laid the foundation of grounded theories. Strauss and Corbin have evolved the approach; see their overview in [10]. Researchers applying grounded theory collect data and extract key points called codes. Next, they cluster codes into concepts, form categories, and finally formulate a hypothesis. In other words, this approach is bottom-up, starting with observations and gradually crystallizing a theory. This way of working seems quite appropriate in a young field as systems engineering with many similar challenges as the social sciences. Charmaz [11] recommends memo writing as a technique in this process from data to concepts. We grow this collection of case studies to facilitate the formation of grounded theories by performing a kind of meta-analysis on them, for example as proposed by Glaser, Strauss, and Charmaz.

Research Methods in Industry as Laboratory

The nature of action research or industry as laboratory complicates this research. The way of doing this type of research requires research methods that fit in the socio-technical context. In a previous publication [12], the author describes the methods that researchers in our program have used in this research so far.

Figure 2 shows a context diagram of the research and many entities that are relevant for the research. If we study how effective a concept selection technique is, then we have to observe and describe the people using them, the process in which the concept selection is applied, the stakeholders and their concerns and objectives, the artifacts used, and the concepts themselves. Researchers have to strive for understanding the causes of success or failure. Is the technique, the embedding process, the people, or some other factor the cause?

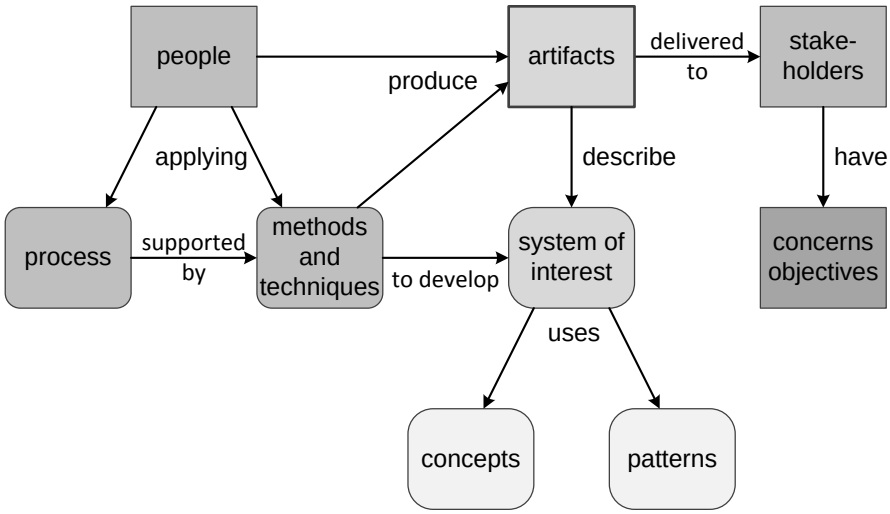

Figure 2. Context diagram with entities relevant for the research.

Research methods assist in data collection and evaluation. These methods can range from free format and relatively informal to a standardized format with more formalized definitions. Examples of free format data collection are open interviews, sketches, and log observations. Examples of standardized methods are formal models, structured reports, and structured data collection. Free format methods are more flexible and adaptable, however analysis and evaluation is difficult; researchers cannot accumulate or compare data without formal definitions.

Systems Engineering Research in Kongsberg, Norway

In this chapter, we report on the research in systems engineering in Kongsberg in the period 2008-2013. In this subsection, we provide background to the specific situation in Kongsberg: the industrial background, education in systems engineering, and the research model based on master projects. Master projects have been our main research vehicle. The cooperation with industry and the structure of the master program facilitated this form of research.

The Kongsberg Industrial Cluster as Laboratory

The Kongsberg industry inherited a strong technology base from the Kongsberg Vapenfabrik (weapon factory) in the second half of last century. After privatization in the eighties, the Vapenfabrik went into a Norwegian version of Chapter 11 for bankruptcy regulations. The stronger parts became strong players in different markets: component production in among others automotive and aerospace, gas turbines, sub sea oil and gas equipment, maritime, and defense. This industry develops and applies complex systems, requiring integral disciplines such as project management and systems engineering. Typical characteristic for most industry in Kongsberg is that the systems operate in harsh environments. For example, sub sea oil and gas equipment operating at depth of 3000m at extreme pressures and temperature ranges, aerospace components and subsystems with lifetimes of 15 years

The Norwegian government, the Kongsberg community and industry and Buskerud University College (BUC) identified Systems Engineering as crucial competence for Norway in 2001. As a result, of national and local government and local industry created the Norwegian Center of Expertise (NCE) for Systems Engineering (SE) as joint effort. They established funding for a 10-year program; see [13].

Master in Systems Engineering at Buskerud University College

One of the main projects of NCE was the establishment of a master study in systems engineering at BUC. The author has described this process in [14]. The goal of the master program is to create an educational path that helps industry to foster new system engineers in 5 to 10 years, rather than the 10 to 20 years in current practice. The result is a master study Systems Engineering that BUC offers in two variants:

Local industry deploys *Industry Master (IM) Students* part-time allowing the students to study part-time. *IM students* need 3 years of elapsed time to obtain a masters title with 2 years of nominal study effort. Typically, *IM students* do not have previous working experience. Since we believe that experience plays a crucial role in developing the systems engineering competence we have introduced this part-time industry involvement. During the study, reflection is encouraged so that students benefit the most from the practical experience in industry.

Part-time students are already working in industry and do their study part-time. Typically, part-time students need at least 4 years of elapsed time to finish their master education.

Master Project Research

All master students have to perform a master project in the last semester of their study. This master project is 30 ECTS[1] or half a year full-time study load. We use the master projects for multiple goals (see [15]) at the same time:

1. To provide value to the industrial employer by working on actual projects,
2. To facilitate students to apply SE in realistic industrial conditions
3. To facilitate the students to make the step from “just applying” to “critical reflection”
4. To verify that students are capable to operate at academic level
5. To create a research portfolio and capability at BUC

[1] ECTS stands for European Credit Transfer and Accumulation System and is a standard across the European Union, see http://www.mastersportal.eu/articles/388/all-you-need-to-know-about-the-european-credit-system-ects.html

Master students have done a major part of the research at BUC until now, during their half-year (full-time) master project. Gradually, we start to recruit PhD and other researchers. The results of this research are promising; we have published thirteen papers at conferences and journals (see http://www.gaudisite.nl/MasterProjectPapers.html).

Figure 1 shows the logical order of steps to define a research project in systems engineering. The starting point is a need for improvement in the field, triggered by an industrial problem. Researchers reformulate the problem into an industrial goal; “where do we want to go” instead of “where are we”. The problem triggers multiple research questions, e.g. how much can method x mitigate the problem? The next step is to sharpen the research by looking for quantifiable propositions, e.g. full requirements traceability will reduce the change request rate after the project definition with 80%. Researchers can use the research questions and the quantified propositions to formulate a hypothesis as basis for evaluation. Often a number of explicit criteria help in such evaluation. Preferably, the research leaves room to study multiple options. The researcher will need some baseline to evaluate. The baseline can be past performance, benchmarking with other projects or organizations, or comparison of different solutions.

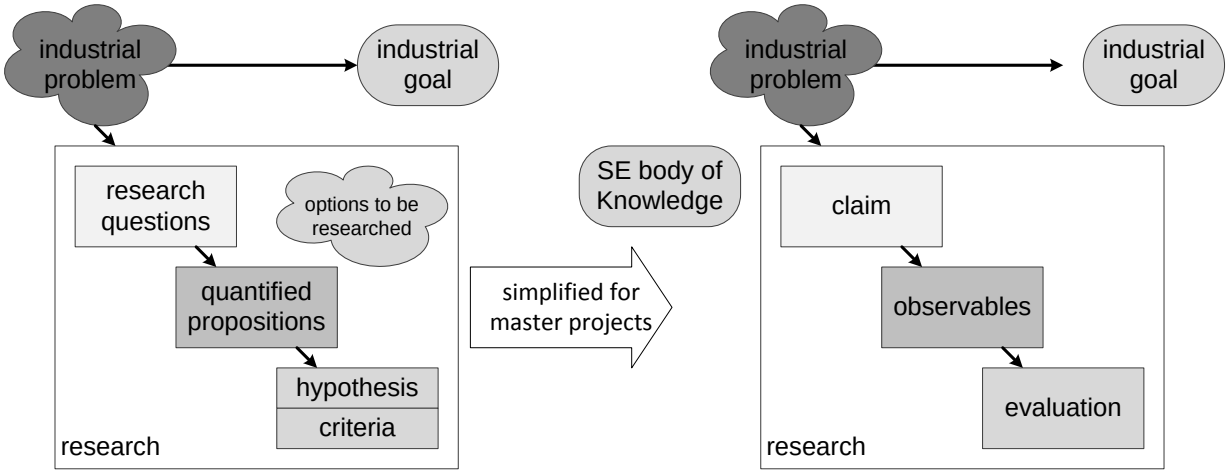

Figure 1. From industrial problem to validated research; left the generic approach, right a simplified approach used for master projects

We simplified the research model shown in Figure 1 left for research done in master projects of six months duration. The researcher looks in the systems engineering body of knowledge for methods or techniques that could mitigate the industrial problem. The master student captures the expected improvement in a claim, similar to the quantified proposition in the generic approach. The next step is that the student identifies observables that can support or invalidate the claim. Students can then evaluate the claim by analyzing the observables. The claim and observables form the core of the master project research. The claim relates to the contribution of the method or technique from the body of knowledge. The observables focus on supporting or invalidating this part of the body of knowledge.

RESEARCH RESULTS 2008-2013

Local industry and BUC formulated a research agenda in 2008. Core in this agenda is the dominating need for robustness and reliability in harsh environments, a common property of most systems from Kongsberg industry. At the same time, industry feels a continuous pressure to respond to changes and to stay competitive. Reliability and robustness have an inherent tension with the need for change or innovation. The general areas of customer understanding and system design facilitate the research field. Some more specific research fields emerged, such as concept selection, and modeling and analysis. Later we have added the even more generic facilitating field of processes.

Figure 3 shows all research projects in the period 2008-2013 mapped on the Venn diagram representation of the research agenda. The circular dots have been brief exploration projects in the various industries to explore what specific challenges the industrial companies have. The academic supervisors have used this insight to supervise master students in the following years.

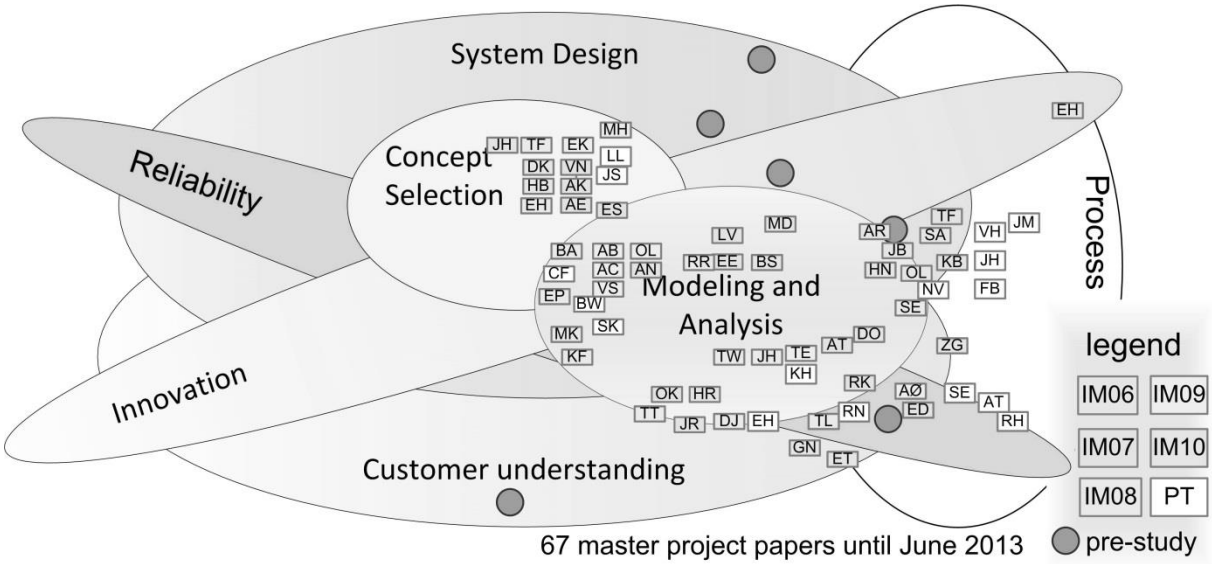

Figure 3. Positioning of research projects on the research agenda.

For these projects, we have counted the key words to provide an impression of the popularity per subjects. Table 1 shows the highest scoring key words. In the next paragraph we will elaborate the research that relates to the highest scoring key words, since these topics have been researched multiple times, allowing us to reflect on any trends.

A3 overview	12
Pugh matrix	10
modeling	9
concept selection	9
requirements management	8
verification	5
validation	4

LEAN	4
interface management	4
integration	4
functional modeling	4

Table 1, Highest scoring key words for the master project papers in the period 2008-2013.

Synthesis of Current Research Results

A3 overviews are based on the work by Daniel Borches [16]. He proposes to use A3 size paper (297x420 mm) to document (partial) architecture overviews. The main idea is that the essence of a topic fits on an A3 and that stakeholders can digest this amount of information in a reasonable amount of time. Borches provides a cookbook that recommends combining at least the following views on one A3: partitioning (or physical model), behavior (or functional model), quantification (or Non Functional Requirements (NFR), or key performance parameters), visual aids, and linking information between these views.

Researchers, who started with the cookbook, typically customized the cookbook to fit their problem. For example, Wiulsrød [17] followed the cookbook closely. However, he composed the A3 stepwise while communicating with his stakeholders. Lindtjørn [18] applied it on a manufacturing production line, using more text and less visualization. Frøvold [19] and Kruse [20] used A3s for validation. Validation requires close interaction with stakeholders, especially in the operational domain. Consequence was that visualization has to be close to that stakeholder world; the visualization was less abstract and more realistic, e.g. using photos.

Vickram [21] built on the A3 experiences of the previous cohorts. However, he combined it with tooling from Model-Based Systems Engineering (MBSE) creating so-called dynamic A3s. The tools generate dynamic A3s from information in the MBSE repository. These tools allow for linking information; users can navigate multiple A3s via hyperlinks. At the same time, users always see the current baseline.

Pugh matrix and concept selection are closely related, since the primary application of Pugh matrices is concept selection. A Pugh matrix [22] is a matrix to evaluate multiple concepts to select an appropriate concept. However, some researchers applied Pugh matrices slightly different, e.g. for component selection. Some researchers applied alternative ways of selecting concepts. However, most papers in these categories apply Pugh matrix for concept selection. In [23], we have captured our initial experiences based on four case studies. The observation in this paper was that the topic Pugh matrix and concept selection is especially popular in the sub sea oil and gas industry. We speculate that the project pressure in this industry, which invites developers to select the most obvious concept immediately, causes this behavior. This paper describes that the experience is that stakeholders appreciate the Pugh matrix. However, at the same time there is resistance, since it takes time, and it differs from current way of working. Lønmo reports in a recent paper [24] “However, the participants in the previous research papers were reluctant to use the matrix in concept selections. On the contrary, this research shows that the Pugh matrix was appreciated amongst the engineers. All the participants wanted to continue to use evaluation matrices, and nearly all will recommend them to other colleagues.” She provides some possible explanations for this more positive reception.

Modeling is a core activity in systems architecting, design, and engineering. The term is used here more broadly than modeling in MBSE. MBSE uses formalized models in for instance SysML to replace mostly verbose specification documents. However, models in the broader sense as used here, are used for understanding, communication, reasoning, and decision making too. Students researching modeling studied aspects such as visualization and effectiveness of the models for understanding, communication, reasoning, and decision making.

Engebakken [25] introduced impact factors to analyze effectiveness of models and to provide guidelines for others when making models. Examples of such impact factors are: close-to-reality, instant recognition, personal relevance, multi-view models, participation, assumptions, iterations, effort and purpose, level of detail, guidance, number of stakeholders, intention, and dynamics. Rypdal [26] and Polanscak [27] build further on the work by Engebakken. Rypdal analyzes how the distance of the stakeholders relates to the kind of model. Polanscak combines modeling with A3 overviews. Stalsberg [28] continues this work relating these impact factors to their role in the phase of the project. The general findings of these four researchers is that modeling is an effective means for understanding, communication, reasoning, and decision making. However, model makers need guidance to make effective models. Lindtjørn [18] reported that effectiveness depends on the skills of the modeler as well. More verbal oriented engineers have difficulties in making effective visual models.

Requirements management is a hot topic throughout Kongsberg industry. There is a clear difference in maturity in systems engineering in general and requirements engineering specifically between companies and business units in companies. The traditional systems engineering domain of defense and aerospace is mature and uses tools like DOORS for requirements management. Sub sea oil and gas, however, is a different world. In this industry standards and regulations from governments, standardization bodies, and oil and gas operators are stacked. Unfortunately, these standards violate requirements management wisdom, such as freedom of implementation, ambiguity, clarity (e.g. the use “may” or “should” rather than “shall”), and scope of requirements.

Tårneby [29] tries to unravel the input requirements in the stack of standards and regulations by implementing a requirements register as spreadsheet. He relates single specific requirements to work packages. Problem is that, even for only one subsea system, the register grows beyond manageability. Tranøy [30] analyzes cost overruns and late variation orders and finds that the tendering and execution process and timing in the oil and gas industry block a proper needs analysis. Consequence is that the incoming requirements do not cover specific operational needs. Hole [31] has similar findings after analyzing non-conformance costs. He proposes a better connection between field study, tendering, and execution in in form of people and documentation.

Hetlevik [32] looks for ways to mature requirements management further in the defense domain by capturing requirements in a more reusable way.

Nysæter [33] and Grinderud [34] apply different tools and formalisms to manage requirements in subsea. The research projects looking into **interface management** also typically look into tools and formalisms. It is too early to draw conclusions on formalisms and tools, other than that MBSE looks attractive for both requirements management and interface management.

Integration, **verification**, and **validation** are relevant in any project business and development of complex systems. The topics are related since typically both verification and validation takes place during systems integration. Tørnlycke [35] and Henden [36] analyzed problems found in the systems integration tests and traced backward to find causes and potential mitigations for future projects. They found that many problems that arise during systems integration could have been detected in earlier test phases. They also conclude that insufficient documentation of specification and design in earlier phases is often the root cause of integration problems. This in itself is no surprise; main question is whether and how these problems could have been detected and mitigated in earlier project phases. Next question is what the costs are in terms of effort, time, and money, and how these relate to benefits.

Øvergaard [37] and Dalby [38] worked on automated testing to reduce testing effort and to increase testing quality. Research question is whether the effort to create and maintain automated testing is in balance with the benefits. Both papers show that automated testing is beneficial. However, in both cases, the project shows that automated testing is far from trivial. Automated testing mostly makes sense if the testing frequency is increased. Neither project could substantiate the benefits sufficiently, since this requires a significant period of using the automated tests.

LEAN is in fact a collection of LEAN techniques and principles, such as late decision making, set-based design, and A3 reports. Despite popularity of LEAN product development, the introduction in day-to-day practice takes more effort than expected. An example is the study by Hansen [39] in the pre-amble of introducing set-based design in her company. She analyzed the opinions and expectations of the immediate stakeholders and compared them with literature. One of her conclusions is "They [the employees] seemingly need clearer guidance, and ask for access to and knowledge about appropriate tools to use in the implementation. There seems to be a great potential for successful implementation provided the employees gain a better understanding of the method."

Functional modeling is a first essential step to understand and explore systems more conceptually. Teachers are well able to convince students of the relevance of functional modeling. Unfortunately, many engineers in practice work intensely in the physical paradigm, close to the realization, without an explicit understanding of system behavior, e.g. in terms of functions. Several students have tried to introduce functional modeling, for instance in the form of IDEF0 diagrams; see for example the paper by Drotninghaug [40]. A bottleneck for functional modeling seems to be that most functional models are quite abstract, distant from the mental world of many stakeholders. She found that "For the employees without Systems Engineering background the tools that provided the most value were the geographical model, the Context Diagram and the Physical Architecture.", which were the models that are the least abstract and closest to their day-to-day experience.

EVALUATION OF INDUSTRY AS LABORATORY

We have applied industry as laboratory five years in the master projects in Kongsberg. The result is that we have 67 master project papers describing cases where the researchers have applied systems engineering methods or techniques in practice. Thirteen of these papers have been published so far. Of

the 67 papers, 18 have been finished in June 2013; we hope to publish four more papers of these recent 18 papers. This means that we publish about 25% of the papers.

We continuously experience the need for a good master project preparation, with proper scoping and identification of a carrier project (e.g. an ongoing project in the company that is willing to accommodate the master project as integral part of the project) and identification of relevant systems engineering methods or techniques that master students can apply for evaluation. We observed some pitfalls and problems:

- Companies that create special projects for master students. Such projects do not fulfill the industry as laboratory paradigm, since the student is more or less isolated from ongoing projects. We estimate that about 10% of the projects are too far outside the main stream.
- Students that select improper systems engineering techniques or methods, e.g. methods that that are too far outside the normal way of working or where the effort is not in balance with expected benefits. We estimate that another 10% of the projects suffer from this problem.
- Dynamics in the company that disturb the chosen carrier or the work of the student. Students regularly suffer from project dynamics. However, in most cases, the dynamics is part of normal practice; good methods and techniques ought to be robust for changes in the context. Students suffer some more from changes in the project timing, which sometimes prevents them to observe expected benefits, since the master project itself has a hard (academic) deadline. Consequence is that the evaluation gets weaker than planned.
- Students that strive too much for a positive outcome. With their engineer's hat on, they need to strive for a positive contribution. However, as researcher they need the opposite drive. Main risk is that students are blind for negative inputs, followed by the risk that the outcome is biased. The academic supervisor has to intervene timely.
- Students and companies that shift the project too far in the process or tool direction. Processes and tools are core assets in systems engineering. However, in the industry as laboratory approach, we favor the application and evaluation of processes or tools in practice, rather than process or tool studies or introduction without application. The application is essential to get some substance in the evaluation.
- Projects so confidential that publication of the results is out of the question. This happens in the defense industry. It also happens in the supplier industry, where the customer does not permit any publication. Sometimes, the researcher can separate and publish the method or technique results without the domain context; loss of context may hamper further analysis of these results.
- Students with high performal capabilities and less linguistic capabilities that have problems in transforming their insights in linear text.
- Well executed projects that are difficult to publish due to a narrow project scope. The findings and data collection may still be relevant for further analysis when the limited scope is taken into account.

The collection of case studies is reaching a size where we gradually hope to harvest slightly broader findings, for example in topics such as concept selection and A3 architectural overviews. Such

aggregation would benefit from standardization of data collection. We have to find a proper balance in minimizing constraints and standardization to facilitate aggregation. The first step in this direction has been a workshop and reader on research methods in the preparation phase of the master projects.

CONCLUSION

The master students in systems engineering at BUC who are working part-time in industry are producing a collection of cases of the application of systems engineering in practice. This collection is a first step to substantiate the actual applicability and value of methods and techniques that we have captured in the systems engineering body of knowledge and that we teach worldwide in systems engineering curricula.

The preparation phase and the problems statements formulated in many papers show abundant needs for improvements in systems development, where systems engineering claims to offer solutions. The needs vary over the companies and their systems engineering maturity. We see the full spectrum of needs from customer understanding and needs elicitation to systems integration, verification, and validation, followed by lifecycle management issues. The practice of systems development struggles with aspects where systems engineering should bring value.

However, main conclusion from these initial case studies is that value and applicability is not self-evident. In general, stakeholders appreciate the application of systems engineering methods and techniques; however, the reception is not that positive that the use of them spreads itself further into the companies.

The research model using master students that have been working in the company and let them practice action research or industry as laboratory has produced a significant number of case studies. With 25% of the case studies actually published, we are creating a collection of case studies to facilitate further theory forming of system engineering

FUTURE RESEARCH

The number of case studies has to increase an order of magnitude to facilitate better substantiation of applicability and analysis of the value of systems engineering methods and techniques. The balance between free format, allowing unbiased observations, and standardization, facilitating aggregation and analysis across cases, needs to evolve, striving for a sweet spot in both aspects. Further theory forming on effectiveness may help in balancing these aspects.

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