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Validation of Systems Engineering Methods and Techniques in Industry

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Abstract

Systems Engineering methods and techniques are mostly taught under the label "Best practices". Unfortunately, for most methods and techniques we have little support that they are good or even best. In this paper we describe an industry-as-laboratory approach that is applied to evaluate methods and techniques in industrial practice. Our students with at least two years working experience in their company choose one method or technique to study in the daily practice in their company. They apply that technique in one or more projects, observe or measure the results, and evaluate the method or technique. In that way we gradually build up a collection of case studies that can be used to support (or invalidate) claims about the applicability systems engineering methods and techniques in different circumstances and domains. In this paper we report our current insights after 40 master projects in 3 years. The choice of methods and techniques so far has resulted in two methods that have been studied at least six times: concept selection by Pugh matrix and A3 reports. We see that using Pugh matrices helps to evolve the thinking about problem and solution. A3 reports are a promising technique to improve communication and discussion.

Keywords: validation, methods, research

1. Introduction to Validation of Systems Engineering Methods and Techniques

INCOSE manages the Systems Engineering (SE) Body of Knowledge (SEBoK) [1] as professional society. The Body of Knowledge and Curriculum to Advance SE (BKCASE) team is doing the work, among others by organizing workshops and by writing papers [2]. SEBoK serves as the foundation for SE curricula. BKCASE is an effort to identify, collect, categorize and disclose SE methods and techniques.

One of the challenges in SE research is to provide support for claims that we make about methods and techniques. We mostly capture experience of senior systems engineers and based on their experiences declare them to be best practices. Another source of knowledge comes from academics and suppliers of

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tools; they develop tools with claims that the tools will help systems engineers. Both categories lack more factual support of their claims. We assert that validation of SE methods and techniques primarily needs to be done in "the field" where these methods and techniques will be used routinely. Research done at universities may validate some of the properties of methods or techniques, such as stability or convergence. However, their effectiveness in industrial practice, when used by industrial practitioners requires an industrial setting for validation.

Boehm et al [3] have been researching the effectiveness of SE in more general terms. They look at questions such as: "How much effort should be invested in SE?" They collected a lot of industrial data to facilitate the analysis. We have chosen a complementary approach to collect factual data about the value of individual SE methods and techniques. Our students do their master project when they have at least two years of experience in their company. The students select a project to work on in the company together with their company supervisor. This project should be a normal project in the company that should be done anyway. During this project we ask the student to *apply*, *observe*, and *evaluate* one SE method or technique, and to capture that in an academic paper. Every master paper is in that way a small factual contribution to substantiate the value of SE techniques and methods in specific circumstances and domains. The Kongsberg industrial cluster allows us to look at several domains: defense, maritime, sub sea oil and gas, manufacturing of automotive and aerospace components, and gas turbines.

Since the SE field is extensive, we ask students to select a project that fits in the local research agenda. In that way we have a higher probability that we obtain multiple cases for the same methods or techniques. Once we have multiple applications of a given method or technique, we can compare them, and we can analyze them together to increase the credibility of findings.

We have the following goals when using master projects for research (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.

2. Master Project Approach

We guide students through a preparation phase of six months before they execute the actual project in five months. At the end of the five months they write an academic paper that is used for grading. We will zoom in on these steps in the following sections.

Preparation Phase. The preparation phase consists of 5 short workshops as shown in Figure 1. In June we explain the master project process in the first workshop. The process is described in <http://www.gaudisite.nl/SEthesisProjectPaper.pdf>. We ask the students in the invitation for the workshop to prepare themselves by generating ideas for the project and the SE method or technique they might want to study. We urge the students to discuss potential projects with their company supervisor. A good project has a clear, not too large, scope for the student. Typically, a project will address part of a system or a function of the system; we call that the case. Students also have to think and talk about the needs of the company; what SE method or technique can be of value for this case.

We ask the students to make a simple plan to let them think about the limited amount of available time, the relations between activities, and the required resources. We do recommend students to plan for a few iterations (problem, solution, and reflection) to avoid that they discover at the end of the project that they misunderstood the problem, or that they lack data for evaluation.

From August onward we let the students work on the abstract. The primary purpose is to force the students through a mental process. Why does it make sense to apply this method or technique on the case? What are the expectations of applying them? What will be your claim in the final paper? What can you observe or measure that will support or invalidate that claim? These questions trigger a process where students have to think about the research approach. We are stretching the students during this process; their world so far has been concerned with learning and doing, not with researching.

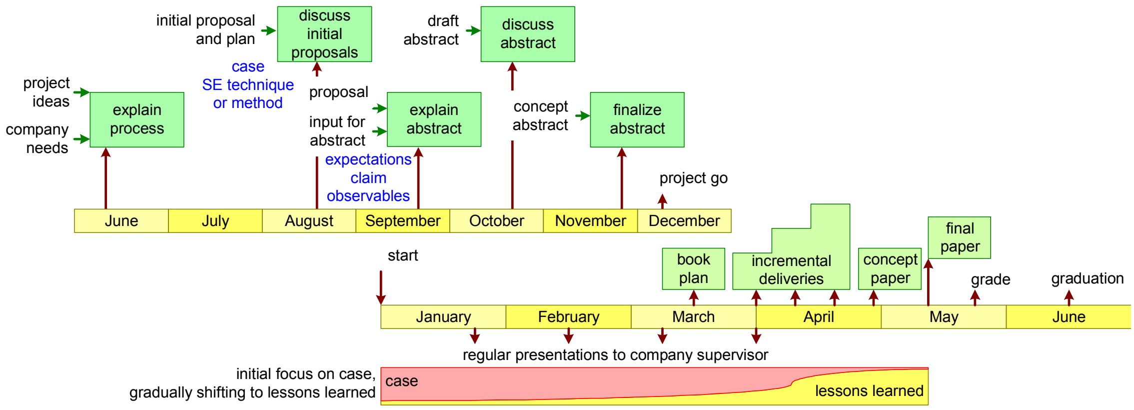

Figure 1. Master project preparation phase.

Research Agenda. Figure 2 shows the research agenda of BUC SE. This agenda has been defined in close cooperation with the local industrial partners. The purpose of this agenda is to provide guidance to research, such that there is focus in the research effort and that results are valuable for the industrial stakeholders. At the same time, the research agenda is kept simple to avoid that it is too restrictive.

Local industry (defense, maritime, subsea oil and gas, gas turbines, automotive and airplane engine components) typically makes products that operate in harsh environments; reliability and robustness are important properties. At the same time, these companies operate in a competitive environment full of changes (regulations, needs, business, technology); hence innovation or responsiveness to change is also an important property. These properties have some inherent tension; reliability is often achieved by maturity and minimizing change. The third research area is more generic system design methods and system modeling and analysis. The Venn diagram shows the same research areas and illustrates the overlaps of the different subjects.

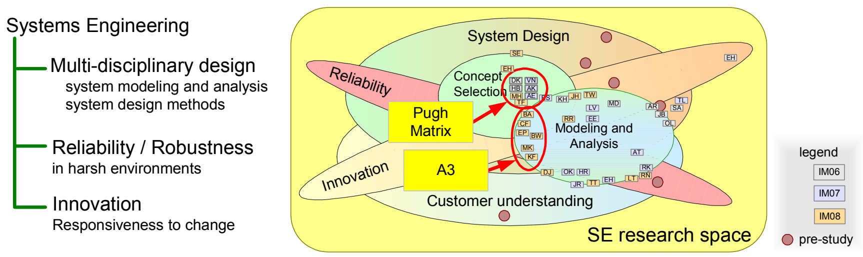

Fig. 2. Research agenda as graph and as Venn diagram; in the Venn diagram the coverage is shown.

Execution Phase. The initial focus during project execution is on the case; see Figure 1. We urge students to present their progress regularly to their company supervisor, with an electronic copy to the academic supervisor. Early presentations will be mostly address the case, e.g. specification, design, analysis, or measurements. One or two slides with reflections help the students to step back from the case. Later presentations gradually contain more reflection, for example captured as lessons learned. Half way the project we ask students for the structure of their final paper, in the form of a book plan. A book plan shows the structure in sections and subsections and gives size indication in the number of pages. The last month of the project is dominated by writing.

Writing the Paper. Most students do not have experience with writing academic papers. We provide them with some guidance when they create their book plan. We demand incremental delivery of the paper itself. Incremental delivery allows early feedback on structure, language, style, and content. This type of case studies has to capture multiple threads: the case, the SE BoK, and the research approach. These threads have some coupling; the challenge is to write a paper such that it is well readable and fulfills academic rigor.

Publishing papers. We inform the students at the beginning that we intend to publish their papers, if the quality warrants such publication. However, we inform them that publication takes time, and that the papers need to be screened by their company before publication. After their graduation we contact the authors of the papers we like to publish. The authors iterate one or a few times with their company supervisors and academic supervisors to remove any confidential or sensitive information without losing the essence of the paper itself. Typical publication outlets for these papers are: CSER, INCOSE symposium, EUSEC, Systems Research Forum, and ultimately the Journal of Systems Engineering.

3. Coverage and Findings

We have graduated 40 students until summer 2011: 8 students starting in 2006, 14 students starting in 2007, and 18 starting in 2008. The distribution of the students over the domains is: 17 students in subsea oil and gas production, 8 in maritime, 6 in manufacturing, 9 in other domains. We have mapped their SE method or technique on the Venn diagram of the research agenda in Figure 2. Every rectangle represents the work of one student. The small circles are pre-studies done in 2008 in preparation of the master projects. A more truthful representation would decrease the size of the rectangles and squares many orders of magnitude, to indicate that every case covers an extremely small part of the research space.

Concept selection by means of Pugh matrices has been quite popular; we have reported these findings in [4]. Six students of the cohort that started their master project January 2011 applied A3s based on the work of Borches [5]. This subject creates a lot of enthusiasm with industrial practitioners. One of the A3 papers won the best paper award of 2011 master project papers at BUC. Another of the A3 student researchers gave a presentation at the Kongsberg Systems Engineering Event 2011; see <ksee.no>. It is too early to report on actual publications. We submitted 3 of the 6 A3 papers as individual papers.

The grading of the papers, on the Norwegian scale, is as follows: **A** (=excellent) Papers are assessed to be publishable as is at a conference or journal, **B** (=very good) Papers are close to publishable, with limited effort publishable, **C** (=good) Paper is OK, but we expect that conferences will not accept such paper, **D** (=sufficient) Paper is acceptable, **E** (=marginal) Paper quality is marginal, **F** (=failed).

We strive for actual publication of papers with grades A and B; in practice, students with grade B often do not want to make the additional effort to publish their paper. Published master project papers can be found at <http://www.gaudisite.nl/MasterProjectPapers.html>. At this moment we have five student papers that have been published. One of the cohort 2007 papers has been submitted. Another A-graded paper from the cohort 2007 contained too much confidential material to be published. The cohort of 2008 scored four As and eight Bs; at this moment eight students (all 4 As and 4 Bs) have the intention to publish their paper; 4 of these planned publications address the use of A3s.

Project preparation findings. The elapsed time of the preparation is long (6 months). Most students need this amount of time to explore cases and possible SE subjects, to discuss these topics with supervisors and colleagues, and to go through the discovery process as described above. Students do not apply SE thinking on their own project automatically. Asking for a problem and need articulation (for their company) is often seen as interesting new approach. Similarly, they do not start to sharpen the master project objectives by formulating a claim and by thinking how they will be able to evaluate such claim. These students did not have any course in their curriculum that addresses scientific approaches, methodology, or reflection. The next cohort with students who started in 2009 does have such course in the curriculum, called Reflective Practice. It will be interesting to see if the later students find this step easier to make than the first three cohorts.

Writing the abstract and guiding the students through these steps helps students to be prepared for their project. In average 9 documents are exchanged per student in the preparation phase. Most of these documents are successive versions of the abstract.

Project execution findings. During the preparation phase we instruct students to start data collection right from the beginning. Some data must be done at the beginning, for example, zero measurements inherently need to be done at the start. Problem, in practice, is that researchers need some time in the problem field to discover what needs to and can be measured or observed. Collecting data for evaluation is difficult for most students. We have to manage expectations here since it is not realistic to expect the same academic rigor of master students who spend 6 months on their project as PhD students who spend three to four years on their research.

Findings of writing the papers. We instruct the students to write the paper incrementally, after thinking about the structure of the paper by creating a book plan. Typically, students need between 5 and 15 incremental deliveries to get to the final submitted paper. Language, style, and structure quality show a wide variation. We have given the students no training in scientific writing; they only get a few documents describing the basic structure of a scientific paper or case study.

Language. In all feedback cycles language issues are addressed. Quite some language mistakes are systemic (e.g., spelling market as marked). Nearly all students are native Norwegians and the academic supervisors do not have English as their native language either. We ask students to look for a native English reviewer at the end of the project.

Style. Students have to get used to an academic writing style; striving for objectivity and avoiding subjectivity. Very common is that we have to eliminate "I"; we often transform that in "we". Students often write in passive voice; active voice is recommended and often more explicit. Word provides clear feedback for both language and style. Nevertheless, we often have to point out Word feedback. Not all Word feedback should be followed blindly. However, in general this feedback makes sense.

Structure. Several cycles are needed to get a logical flow in the paper. The fact that this type of projects has multiple threads that need to be described gives multiple options for the structure of the paper. Some students ask for the standard recipe. Others follow a standard scientific template that might not fit well to this kind of case study. Supervisors may lose overview of the structure after several iterations of language, style and content.

Content. Often we have to make them aware that they have to write for the readers of the paper. For instance, they will have to give sufficient introduction to the domain, the company, and the system since most readers will have a different domain background. Several feedback cycles are needed to transform the text into coherent arguments. Most common struggle is to get the evaluation well supported. This requires a clear problem statement or research questions in the beginning, some "hard" observations, and a well formulated argument. Since often one or more ingredients are missing (often the observations are "soft"), the evaluation tends to become talkative.

The writing is typically concentrated in a 3 week period. With in average 10 increments we need a cycle time of about 2 days for the submit-read-annotate-update cycle. The writing period is an intense period for the students and for the academic supervisors.

4. Evaluation of Master Project Approach

We formulated five goals for the master project, which we will discuss one by one:

To provide value to the industrial employer by working on actual projects. This varies per student and per company. The experience of the first year was that some companies viewed the master project as a student project and looked for something stand-alone outside the main flow of work. We now communicate early that we need projects that are part of the normal work in the company and well-integrated with other projects. In general, most projects fulfill that need. However, the SE method or technique that is chosen is sometimes too much "push", rather than need based. For example, in all companies "requirements" can be seen as an area of improvement opportunities. However, as long as these companies do not see the need for such improvement themselves this topic is "push". The result is that companies may not perceive added value of the student's work. We will have to emphasize the needs analysis even more in the preparation phase.

To facilitate students to apply SE in realistic industrial conditions. See previous discussion. Nearly all students have done their project in realistic industrial conditions in the cohort that started in 2008. The main risk is too much emphasis on process or method. The difficult mental step that student and company supervisors have to make is the duality of the master project. Our ultimate goal is the method-side; how well does the method or technique work in industrial practice? However, to be able to make such evaluation, students spend most time on the case, applying the method or technique. If students stay in theory and only read and discuss literature, then we fail in this objective. We did not strike the right balance here in 3 of the 18 students of cohort 2008.

To facilitate the students to make the step from "just applying" to "critical reflection". This proves to be a significant challenge that relates to the core of the research approach. We described the struggle of the students to formulate a claim and to define what can be observed and measured to evaluate the claim. Critical thinking is required to get from the level of "feeling that it works" to actual evaluation. Since this capability is core for SE, we have to question the mandatory curriculum: do we sufficiently train our students in critical thinking?

To verify that students are capable to operate at academic level. Our interpretation of academic level is that students are able to address and contribute to complex problems in why (rationale), what, and how, and that they are able to reflect on the approach to the complex problem. The result is captured in the academic paper that has to show these aspects in the multiple threads. The grading shows that all students fulfill this criterion. We have to clarify that students are selected; a Norwegian C as average is the minimum.

To create a research portfolio and capability at BUC. With 5 directly published papers, one submitted and one aggregated paper from the first 24 students we have a good harvest and a nice start for a research portfolio. Nevertheless, we need more substance in the evaluations that may require the effort of a few PhD students in addition to the master students.

5. Future Research

Research in Systems Engineering is relatively young. The core challenge is to find academic methods to validate methods and techniques. We will need instruments to observe, such as interviews, and standardized forms, and we need ways to "harden" the inherently soft information, such as metrics. Ideally, metrics for success are baseline business metrics, such as value, profit, effort, project duration, predictability, and all of these sustainable over a longer period of time. Longer research projects are needed for this type of metrics. Next challenge will be to argue what contribution comes from SE methods. Evaluation of past projects will be translated in improved instruction for the preparation. Ultimately, we might have to adapt the curriculum based on these evaluations. The future projects have to be evaluated to assess the effectiveness of new mandatory courses such as Reflective Practice, and the improvements to the preparation.

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