Creating an Academic Systems Engineering Group; Bootstrapping Systems Engineering Research

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Abstract

Systems Engineering is a young field where most systems engineers are self educated older engineers. The large need for systems engineers in industry necessitates the creation of academic systems engineering groups where education and research is combined. We describe in this paper the ongoing effort in Norway to create such an academic systems engineering group as part of the Norwegian Centre of Expertise (NCE) for Systems Engineering.

We briefly discuss systems engineering as competence and the educational program. The remainder of the paper elaborates the research in systems engineering. We discuss the (im)maturity of this type of research in relation to the research methods that can de used. We describe the specific bootstrapping process that we follow in Kongsberg. The first step in the bootstrapping process is the establishment of a research agenda as joint effort of industry partners and academic staff. Based on the research agenda multiple small research projects are performed that prepare the execution of the master student research projects. We also discuss the more generic outcome of the first set of small research projects.

Keywords - Systems Engineering academic, research, incremental, master, project.

1 Introduction

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 the Norwegian Center of Expertise (NCE) for Systems Engineering (SE) was created as joint effort of national and local government and local industry. Funding for a 10-year program was established; see [3] and http://ekstranett.innovasjonnorge.no/templates/Page_Meta____56544.aspx.

One of the objectives of NCE-SE was to establish education for future systems engineers. It was identified that current system engineers have achieved this role by working in industry for many decades. The challenge was formulated 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 education should consist of a contribution to existing bachelor education, a new Systems Engineering master, supportive courses for industrial practitioners and PhD education in Systems Engineering. NCE-SE chose a stepwise approach, where the initial focus was on the new Systems Engineering master. The birth of this master was eased by cooperating with Stevens Institute of Technology (SIT) from Hoboken NJ in the USA, especially with the School for Systems and Enterprises (SSE) [14]. SSE has a well established master education in Systems Engineering [15]. The cooperation with SSE resulted in 2006 in the start of a master study Systems Engineering provided by SSE in Kongsberg.

The next milestone is the accreditation of BUC for a master's degree in Systems Engineering. This master relies heavily on the Stevens program. However, courses are added that have specific value for the Norwegian industry and that build on the existing competences. Accreditation in Norway is performed by "Nasjonalt organ for kvalitet i utdanningen" (NOKUT). This independent organization provides a complete template for application [10]. This template covers educational program, research program, staff, and (educational) systems and infrastructure. BUC have sent their application to NOKUT Mid 2008 [1]. The accreditation process typically takes ½ to 1 year.

In this paper we will discuss the set-up of the educational program. Main focus, however, will be the creation of the research program.

2 Systems Engineering Competence

Systems Engineering as competence is young. System engineers are found in industry, where complex systems are created in large development projects. Systems Engineering is not a classical discipline, such as mechanical engineering, control engineering or software engineering. Major differentiator for Systems Engineering is its multi-disciplinary nature. System engineers focus on the system itself, where system properties are the result of the resulting interaction of many mono-disciplinary design decisions. Next differentiator is that the context of the system, where is the system operated, by who, et cetera, needs to be understood by system engineers. Both differentiators make Systems Engineering "broad".

INCOSE is most active in capturing and promoting Systems Engineering. The roots of INCOSE are mostly in the military and aerospace domain. However, many of the methods and techniques from this domain are valuable in other domains, such as health care, automotive, manufacturing, industry, et cetera. INCOSE is a professional society, where most members are practitioners. In the last few decades tens of academic groups have been formed at major universities working on Systems Engineering. From academic perspective this is very young. Most systems engineers in the field are autodidacts, with decades of engineering experience. The staffing of successful academic groups is often a mix of reflective practitioners and open-minded academics. Most of the Systems Engineering knowledge is implicit, hidden in the heads of thousands of practitioners in the field.

The systems engineering competence is founded on the more classical disciplines. The system engineer obtains a framework of methods and techniques by doing one of the engineering disciplines. During this education mathematical methods and working with rigor are part of the standard curriculum. To this disciplinary foundation system design, systems thinking and contextual methods and techniques have to be added to obtain the systems engineering competence.

One of the challenges for systems engineers is the balancing act between rigor, working towards proven solutions, and coping with uncertainties, unknowns and the complexity of heterogeneous problems and solutions. To phrase this differently, the balancing act between *deep* well-defined analysis and *broad* heterogeneous synthesis. This field of tension is core to the systems engineering competence.

3 Educational Program

Contribution to technical Bachelor studies is achieved by offering system design as course in the bachelor program. The objective of this course is to make bachelor students aware of systems engineering as competence by showing actual cases and by teaching some systems engineering methods and techniques. This course follows the standard bachelor scheduling, half day Systems Design during a semester.

The **Master study** Systems Engineering is offered in two variants:

Industry Master Students are part-time deployed at the local industry and study part-time. They need 3 years of elapsed time to obtain a masters title with 2 years of nominal study effort. Typically industry master students don't 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 to 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.

The format for courses is adapted to facilitate this concurrent work and study model. Courses are teached in burst mode: 5 consecutive days. After these 5 days the students have to work part-time on a course related project for the duration of 10 weeks. This schedule facilitates also more remote students and teachers, since they only have to be at Kongsberg during the one week course. The mixture of teaching, exercises, and practical work is complemented with active attention for reflection. This combination follows the requirements described in [6]

The one week courses of the Master program are also open for industry participant who only want to follow that subject as course. These participants don't study for credits, so they don't do any project after the course. The class room of the master study is filled with three types of students: *industry master students*, *part-time students*, and *one-time industrial participants*.

For **PhD studies** a separate accreditation is required. NCE has funding for a limited number of PhD students, who work at Kongsberg, but have a promoter at one of the Norwegian Universities, such as the technical University in Trondheim (NTNU). The longer term plan is to obtain accreditation for PhD studies as well.

4 Systems Engineering Research

Research in Systems Engineering has to deal with the fact that still most of the methods and techniques are implicit. Attempts to improve and claims of improvement are quite difficult due to the implicit nature of the knowledge base. A significant amount of research is required to change this state of affairs: to make the implicit systems engineering knowledge explicit.

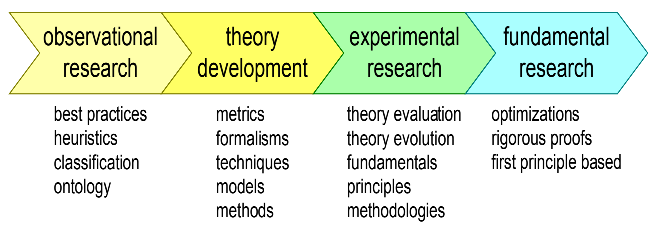

Figure 1 - *Phasing of research.*

Figure 1 shows how disciplines often go through different phases of research. In very young fields the research starts with observations. For Systems Engineering this includes *best practices*, and *heuristics*. A good example of heuristics can be found in [13]. Part of the observational research is the ordering of information, *classification* and defining *ontologies,* as first step in finding structure. In the next research phase theories are developed with amongst others *metrics*, *formalisms*, *techniques*, *models*, and *methods*. The Boderc project [7] used FTMT (*formalisms*, *techniques*, *methods*, and *tools)* as framework for the research. Availability of methods and techniques opens the possibility of experimental research to *evaluate* and *evolve* theories. A foundation can be established with *fundamentals*, *principles* and *methodologies*. As last research phase theories and methods can be *refined* and *optimized*, *validation* can be improved to the level of *proof* and explanations can be based of *first principles*.

Many more conventional disciplines have research methods that fit in the experimental or fundamental research phases. Systems Engineering, however, is still in the early phases of observations and some theory development. The difference in phase and research methods may explain problems in communication and assessment between well-established disciplines and Systems Engineering. From the perspective of well established disciplines Systems Engineering research is sometimes judged to be vague and with little rigor. However, once we realize that we are still developing the baseline, then it becomes clear that it doesn't yet make sense to apply mature research methods to an immature field of research.

The Embedded Systems Institute (ESI) introduced the industry-as-laboratory approach, as proposed by [11] for Software Engineering, for Systems Engineering research [5]. All large scale projects of ESI follow this approach. The first results are [7], [16] and [4]. The industry-as-laboratory approach is especially an attractive research models for the young Systems Engineering field.

5 Bootstrapping Systems Engineering research in Kongsberg

One of the prerequisites for accreditation is the presence of ongoing research to ensure the academic quality of the educational master program. Since no coherent Systems Engineering group did exist in Kongsberg this research program had to be build from scratch. Of course this research program should be based on the strengths present in Kongsberg and should also be beneficial to the participants in NCE.

While hiring the first professor we decided to build the research program incrementally in close cooperation with the Kongsberg industries. We also decided to build on the ESI experiences with the industry-as-laboratory approach. The complete sequence of bootstrapping steps is:

1. Formalize regular meetings with industry representatives at the level of competence or technology management.
2. Write a preliminary research agenda as starting point for further iteration
3. Full day workshop with industry representatives about Systems Engineering as competence and the preliminary research agenda
4. Update and fine-tune research agenda based on workshop
5. Visit individual companies to understand their particular circumstances and needs
6. Write proposal for small (~5 person days effort) research project per company
7. Perform small research projects, often involving 1 or 2 days of workshop with company experts.
8. Make presentation of results of the research project and identify potential slightly bigger research projects
9. Present results and discuss follow-up, including next research phase.
10. Initiate master projects.
11. Broaden the base by involving the other engineering disciplines at Buskerud University College
12. Initiate collaborative research projects with external funding

Part of this sequence is iterated, where the size of the research projects is slowly increased. The first small research projects are performed by the first professor. The later research projects are a joint effort of industry employees, master students, PhD students and staff. The second iteration of research projects will mostly be done with students who started the master study in 2006. By starting the education program with SSE in 2006 we have created a pipeline of master students that will do their thesis project from end 2008 onwards.

We expect to gradually involve PhD students in the research projects. Note that a PhD based research project (4 years) is significantly larger than the master thesis project (half year).

5.1 Buskerud Research Agenda

The initial research agenda written in step 2 proposed three focus areas for the research agenda:

1) Systems engineering in general and system modeling and analysis
2) Reliability and robustness in harsh environments
3) Agility

This initial agenda left the possibility open to add one more focus area based on the workshop. The reasoning behind this agenda is that all industries in the Kongsberg area make systems that operate in harsh environments (satellites in space, missiles and other defense systems in all weather conditions and during war, components in airplane engines, sub-sea equipment et cetera), and that have to be long living and reliable. One of the tactics that is being followed to reach this level of reliability is by being extremely conservative and by using continuous improvement. This tactics is valid, but it is rather rigid when changes are needed. We used the term agile as opposite to rigid. During the workshop it became clear that the term agile was too much associated with the term agile as fashionable in software [2]. The focus area was formulated more neutral to address the underlying rationale more properly into *Responsiveness to change/innovation*.

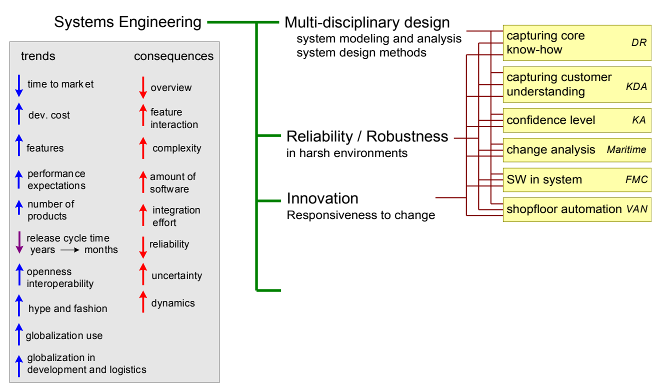

Figure 2 - *Buskerud research agenda in relation to small research projects.*

The reworked research agenda is shown in Figure 2. This figure also shows at the left hand side what trends trigger the relevance of the chosen focus areas. At the right hand side the small research projects are shown and their relation with the research agenda.

The initial research projects are company specific, but they all fit in the bigger picture of the research agenda. The consciously chosen order is to first do company or industry specific research, followed later by generalization and multi-domain validation. In other words we start with observational research in multiple domains. From specific observation we try to see structure and order that can help us to formulate theories. Slowly we will move from specific observations to more generally useful methods, techniques, models and formalisms.

5.2 Small research projects

The small research projects defined in step 6 and performed in step 7 are under way. We have added one more company in Sweden where the design challenges fit well in the research agenda. We will first briefly discuss the research questions and objectives for the first set of small research projects.

Energy equipment
To obtain clear insight in *What is the core know-how of his company?*
How can this know-how be captured to:

- Faster instruct new employees
- Prevent loss of information when current generation of engineers retires
- Serve as common reference for distributed engineering
- Start the creation of supportive, more domain specific models

This set of questions creates work for multiple master or PhD students in the near future.

Component manufacturing 1
To obtain clear insight in *"How to reach desired confidence level when introducing new technologies or concepts with low effort and short duration?"*
To facilitate improvement by a best practices team
Components have long life times and are deployed through a long value chain. The reliability of these components is determined by several techniques, such as Accelerated Life-time Testing (ALT) and Stress Testing. Actual reliability depends on many factors in the usage context, such as load, operating conditions, and maintenance. The challenge with introduction of new technologies is to ensure quality during the long life time in many different circumstances. This research project resulted in models of the context, life-time, life cycle and all related information flows. Follow-up projects will zoom in on how to acquire relevant data, how to analyse, how to use this information to create better components.

Component manufacturing 2
To obtain clear insight in *"How to streamline production by shop-floor automation?"*
To facilitate stepwise productivity improvements through shop-floor automation
To identify impact, risks, and means of introducing shop-floor automation
The actual manufacturing of components is done in halls full of manufacturing and testing equipment. Human operators and supervisors control this highly physical manufacturing process. At the same time ERP systems handle the information side, such as logistics and financial aspects. These two worlds are quite separate, but get much more related when shop floor automation is introduced: the harsh reality of the physical world suddenly starts to intrude in the virtual world of IT systems. Will the total system (hardware, IT, and humans) be sufficiently reliable and robust?

Sub-sea equipment
To obtain clear insight in *"Current status of software development in relation to the system and the expected impact of the growing amount of software development."*
To facilitate improvement of software development and the relation of software development with the development of products and the execution of projects.
The sub-sea environment is a harsh environment, where large physical systems are used for oil and gas production. In recent year more and more software is used within the equipment for monitoring and control. What is the impact of the increasing amount of software on the system, especially on characteristics like reliability? How to evolve current processes and design to cope with the increasing amount of software?

Defense and aerospace
To obtain clear insight in *"How is the understanding of the customer (needs, operational conditions) captured today, what are the issues, where are potential improvements?"*
To facilitate cross-fertilization of experiences across divisions
The defense and aerospace domain is the origin of many systems engineering methods. However, this domain is changing rapidly. In the past the government as customer provided an extensive specification that had to be realized after a successful tender. Today the trend is to tender the problem rather than the solution. The consequence is that the providers need a much better understanding of their customer.

Maritime
To obtain clear insight in "*Changes and their impact; What are origins of change, how and when are changes realized, what is the impact of these changes?"*
The projects in this business rely on the re-use the core functionality of the domain. Sharing components over multiple projects is a balancing act between standardization and customer specials when needed. Changes impact the reliability and effectiveness of the products and may impact the efficiency of sharing components.

Semiconductor equipment
How to connect customer needs to design decisions when new technology is introduced.
This company developed a new process in the chain of semiconductor process steps. The company also produces similar equipment operating in a mature market. The challenge is to create a new product, based on the existing product that performs the new process. Target customers have to be well understood to make the appropriate design decisions for this new product.

We have discussed a seemingly heterogeneous set of domains and research questions and objectives. Based on previous research work [8], we have formulated a set of assertions. We have used our research agenda to observe in all these different projects how our assertions work. These assertions are:

1. Multiple views are required to understand the problem and potential solutions
2. Fast iteration over the views helps to obtain the overview and to identify issues to be elaborated
3. Time-boxing helps the iteration and prevents from being stuck in one particular aspect
4. Simple models make problem and potential solutions more tangible: better communication, and more discussion
5. Visualization driven by the problem statement facilitates sharing and discussion
6. Quantification forces to be concrete and specific.

In all projects techniques have been applied or are applied which are derived from these assertions, building on previous research.

5.3 Master projects

In the 6th and last semester of the master program the students have to do a systems engineering research project on a case in their company, step 10 of the bootstrapping sequence. The project follows *SDOE 800 Special Problems in Systems Engineering* from Stevens Institute, [9] shows specific guidelines for the BUC master students.
The first step in preparation of the master project is to select a case that is of interest both for the company as well as for the research agenda. The next step is that the students have to write the abstract for the paper they have to produce at the end of the project. We have copied this way of working directly from Stevens Institute, see [12]. Our experience is that writing an abstract up front is quite challenging for the students, but also very valuable as preparation. The students are forced to think about the research area, the justification for this subjects, and the expected outcome in terms of lessons learned.
At the moment of this writing the first group of 8 students is working on their projects.

5.4 Broadening the research base

Systems engineering in practice is always applied together with other engineering disciplines. For the industry in the Kongsberg area systems typically the following engineering disciplines are involved:

- embedded systems (hardware and software design, mostly the virtual world)
- control engineering (control by means of actuators and sensors, interaction with the physical world
- mechanics and materials (the physical world)

Buskerud University College has been active in these same disciplines. We are extending the research agenda to include these three disciplines (step 11). In this way we hope to give the research portfolio more body.
Here we hit the next phase of the bootstrapping process, step 12, find funding for research projects. We will deploy the same stratgey again, start small and stepwise increase the scope.

6 Summary and Conclusion

We have discussed the systems engineering competence and what is needed to get accredited for a Master program Systems Engineering. Systems Engineering is a young field, integrating many disciplines. One of the prerequisites for accreditation is an ongoing research program. Research in Systems Engineering by necessity has to be done in close cooperation with industry. We have chosen for the industry-as-laboratory approach. This approach facilitates to observe actual practice and to observe the impact of systems engineering methods and techniques in practice.
The research program is *bootstrapped*, the program is created incrementally. We have discussed the current status with 7 ongoing small research projects. We have shown that despite the heterogeneous set of domains and problems we can do Systems Engineering research with a common set of assertions and related techniques. We also described the other ongoing steps to broaden the base of the research program.

7 Acknowledgments

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