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Teaching Systems Engineering for Students – Experiences from the Swedish Education System

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Abstract. Swedish industry perceives a need for systems engineers due to the useful skillset they develop. However, teaching and providing educational paths for undergraduate and graduate students is a challenge in the Systems Engineering (SE) field. There are several structural and practical challenges to enable education in SE, related to the wide scope and emphasis on *thinking* as opposed to *doing*. Additionally, managing broad engineering programs from a faculty perspective is challenging due to the multi-disciplinary nature required in teaching. In this article we discuss the nuances of providing educational opportunities for SE based on our experiences in implementing a 5-year Integrated Master of Science in Engineering Program in Sweden. We provide our experiences and lessons learned from managing the SE program, while providing an overview of the program and its rationale. These findings can be used to strengthen future educational initiatives to support the development of SE knowledge while transferring experiences from the Swedish system to a wider audience. We discuss our findings through the lens of the future education of systems engineering, emphasizing what changes are expected to meet the needs of the future and the principles we will strive for going forward.

Keywords. Education, Systems Engineering, Experiences, Lessons Learned

Introduction

Systems Engineering (SE) is a holistic and multidisciplinary engineering approach applied across the entirety of a system's life cycle (INCOSE, 2023). SE assists practitioners in managing risk found in systems development through a holistic view on development. As modern systems increase in complexity, SE becomes an attractive discipline in engineering in many industrial segments. This is partially due to SE merging both "hard" aspects of natural sciences with "soft" aspects of social science (Haberfellner et al., 2019). This merger is realized largely through the concept of "systems thinking" (Arnold & Wade, 2015). As systems become more complex the need for methods to reason about complexity becomes ever more important. Likewise, the "big picture" in systems design becomes necessary to capture adequately, across the entirety of a system's life cycle. Providing SE education is therefore becoming highly relevant for engineering education. This need is also reflected in the International Council on Systems Engineering (INCOSE) 2035 vision for SE (INCOSE, 2022). Additionally, it is often expressed that the educational opportunities for SE are currently lacking (De Saqui-Sannes et al., 2022).

Swedish industry expresses the wish to hire systems engineers due to industrial emphasis of SE concerns, but it is challenging to meet these demands through education. The same challenge has also been discussed in previous experiences (Muller & Bonnema, 2013). These experiences can be directly or indirectly mapped to the core tenets of SE, namely a holistic and multidisciplinary approach to engineering across a system's entire life cycle (Kossiakoff et al., 2020). Meeting the educational needs for such a set of skills within a 3–5-year educational span is challenging. This poses foundational challenges for SE as a discipline, where it is challenging to provide the necessary basic education while there is a growing perceived need from industry (De Saqui-Sannes et al., 2022). While the large scope is one source of challenges in educational design, the teaching of critical thinking and otherwise abstract and complex reasoning is another. Providing the necessary collection of courses catering to the natural sciences, while simultaneously providing opportunities for collaborative systems design courses is necessary to truly capture the essence of SE. However, this results in an overall compressed study plan that requires collaboration across several parts of a university as compared to "traditional" engineering programs.

In this article we discuss and provide our experiences and lessons learned on the implementation of a 5-year SE program in Sweden. By extracting this information, we hope to provide valuable feedback to the community for the continued development and improvement of SE education, while also providing an "inside look" to the nuances of Swedish SE education. In particular, we provide a holistic overview of the program and its course construction, in addition to notable choices in program construction. The rest of this article will present necessary background and related work for education of SE, in addition to an overview of modern higher education systems. We then provide a discussion on an SE program developed and launched in Sweden and discuss our experiences in managing this educational program. Finally, we provide our lessons learned and discuss how they can assist in future development and management of SE programs.

Background and related work

SE is often associated with domains such as aerospace, energy systems, automotive, railway, etc. (INCOSE, 2023; Cederbladh et al., 2024). The discipline is often viewed through the ISO/IEEE/IEC 15228 life cycle standard. In fact, the INCOSE SE handbook (INCOSE, 2023) is structured after the standard, using the life cycle stages defined in the standard as a means of structuring the handbook. Since the scope of SE is large, specific standards are often leveraged at specific stages and for specific domains. SE as a discipline instead offers a means of capturing "a big picture view" to assist with decision-making (Haberfellner et al., 2019). Indeed, SE is often differentiated from other engineering disciplines as a means of *making decisions* instead of *creating solutions*. As a result, the skills required for a systems engineer are both deep but also necessitate a broad knowledge base. Additionally, skills not related to "traditional" engineering disciplines are necessary, such as project management (Kossiakoff et al., 2020). Pragmatically, SE is often viewed as a process and standard based discipline to support communication and alignment with various stakeholders. The overall goal of SE is the continued risk management of a system during its life cycle (INCOSE, 2023).

In the INCOSE 2035 SE vision one of the main "paths" is the need to strengthen education and opportunities for education. The vision states: "*SE embedded at all educational levels and across disciplines supported by innovative education and training approaches*" (INCOSE, 2022). In our case, we are mostly interested in the aspect of undergraduate studies, that is, education on the bachelor's and master's levels. While other aspects are important, such as life-long learning or practitioner education, we leave those concerns out of this article, at the same time we recognize they are vital to SE and are positive to expansion in those areas as well. The current status for education in SE has been reported as lacking (De Saqui-Sannes et al., 2022). Specifically, it is recognized that there are few opportunities to attain the skills necessary for SE from higher education, threatening the educational aspects of SE. Considering the vision for the future, where complex technologies like Artificial Intelligence (AI) and model-based approaches are expected, the status (and need) of education is more pressing. Delivering an educational program to meet the needs of current and future SE is therefore an important yet challenging scope. There is a need to align and harmonize current educational efforts, while at the same time introducing aspects of teaching for emerging technology, necessary to meet the future needs of industry and society.

There have been several works that have discussed the issue of implementing education and SE. In fact, the challenges of teaching SE were already reported over two decades ago (Foster et al., 2001). Foster et al. identified that while the need for trained SE practitioners is rising, the available teachers are sparse. At the same time, funding SE programs is challenging as it is cross-disciplinary. These findings have been re-confirmed, in terms of scoping studies (Caldwell, 2007), providing adequate educational profiles (Gonçalves, 2010), and gap in the existing SE curriculum to adopt Model-Based Systems Engineering (MBSE) (David et al., 2019). At the same time, it has also been identified that SE is a useful discipline to support other engineering disciplines through its holistic perspective (Kossmann, 2018). Nonetheless, the scope required to truly "practice" SE is often perceived as too large for university courses (Caldwell, 2007). Furthermore, it has been reported that "active learning" is an enabler for SE (Muller & Bonnema, 2013). Enabling active learning for SE realistically involves some form of group projects, possibly letting students play different roles to simulate collaboration in industrial scenarios (Muller & Bonnema, 2013). Another weakness of SE education is that it is challenging to market to students due to the large and often intangible scope (Foster et al., 2001). The intangible scope is also reflected in the education itself, where students might find it challenging to study an engineering discipline where there are seldom well-defined problems or "right answers" to figure out (Muller & Bonnema, 2013). There has been recent reporting on the joint creation and management of system design courses between industry and academia with success (Bengtsson et al., 2024). Highlighted benefits in this work were the collaboration between teachers and students, and the "hands-on" work. It has been identified that "capstone" courses are useful in the teaching of SE (Herzog et al., 2018). Capstone courses are collaborative courses where students drive projects, promoting active self-learning among students with a high feeling of "ownership" of the course work.

The Swedish higher educational system

Higher education (and research) in Sweden is required to be conducted efficiently and have high quality in international comparison. The higher education shall lead to business competitiveness, the development of the society and welfare, in addition to addressing Swedish and international societal challenges (Regeringskansliet, n.d.). In addition to these high-level goals, each type of engineering program needs to fulfill national learning objectives. Högskoleförordningen, 1993:100, specifies all requirements for Swedish higher education objectives. Therefore, the aim and scope of education in Sweden is relatively well defined which imposes certain restrictions on the flexibility during the design and operation of education.

The higher education in Sweden provides several types of engineering programs for students (2-, 3-, 4-, or 5-year programs). The most relevant are Bachelor (three years), Master (bachelor + two years), "Högskoleingenjör" (three years), and "Civilingenjör" (five years or three + two). Bachelors and Masters are internationally recognized, and "Civilingenjör" and "Högskoleingenjör" are often seen as equivalent from an international standpoint, even if that is not the case by Swedish law. All four types above require showing deep knowledge in the selected engineering orientation while considering scientific, societal and ethical aspects. The five-year programs (Master and "Civilingenjör") have additional research-related learning objectives. Though, the main differences between the four types of programs above concern the many more requirements set for the two educational programs intended for engineering at companies, "Högskoleingenjör" and "Civilingenjör". These programs require additional skills in mathematics and natural sciences, independence, creativity, critical thinking regarding technical solutions, modeling, simulation, teamwork, collaborations in groups, and showing ability to develop and design products, processes and systems while considering human needs and factors as well as economic, societal and ecologically sustainable constraints. Thus, these two programs fit well together with the requirements set for a good systems engineering program already at the "basic" requirements set by the Swedish educational system due to the emphasis on engineering in the wider societal context.

Higher education in Sweden is often primarily funded through government funding. This funding is based on several factors, and largely a matter of political decisions in addition to the level of local supply and demand of educated personnel on a regional scale. In the Swedish education system, funding for universities is provided based on number of students enrolled, in addition to the performance of students enrolled. Performance is often counted in terms of credits completed equivalent to a full-time student's expected credits per year, summed for all students per year in terms of completed course credits divided by the expected number of credits for all students (the sum of accomplished credits by all students during one year / one standard year of full credits for one student). A consequence of this economic model is that engineering students are generally undesirable from an economic perspective. Partially because a similar amount of funding is given to an engineering student from the government compared to other students, while generally being much more costly to fund (e.g., due to lab costs). Additionally, engineering students are among the least likely students to graduate "on time". In Sweden it is common for engineering students to delay completing their degree, in related engineering programs only around 20-25% of engineering students graduate when expected (i.e., 3 or 5 years after enrolling). Nonetheless, Sweden (and many other countries and regions) are in a deficit when it comes to engineers in the workforce, and the demand is only increasing. Therefore, political decisions are more recently encouraging STEM (Science, Technology, Engineering, Mathematics) education, and more specifically engineering to meet this demand. There is also a large push from industries in Sweden to improve and increase students' education to meet the same demands.

The educational program at a glance

The program we will use as our "running example" is a "Civilingenjör" program with the theme of dependable systems engineering. The program consists of 5 years of study. Each year is divided into 4 periods of roughly 10 weeks of study each (called semesters), where students are recommended to study two courses in parallel. It should be noted that while we offer a set of recommended courses, the requirement for a degree is completion of a master thesis in addition to several "relevant" courses counted towards a list of subject areas with a sum of 300 credits, introducing some flexibility. The program is provided in a snapshot view in Figure 1.

	Year 1		Year 2		Year 3		Year 4		Year 5
Semester 1	Vector algebra 7.5 credits, first cycle	Systems engineering in context, 7.5 credits, first cycle	Measurement engineering 7.5 credits, first cycle	Statistics 7.5 credits, first cycle	Quality engineering 7.5 credits, first cycle	Information security 7.5 credits, first cycle	Embedded systems I 7.5 credits, second cycle	Control theory 7.5 credits, second cycle	Dependable systems project course, 30 credits, second cycle
Semester 2	Programming 7.5 credits, first cycle	Basic electronics 7.5 credits, first cycle	Human factors in systems 7.5 credits, first cycle	Architectures and communications for embedded systems 7.5 credits, first cycle	Electrical measuring systems 7.5 credits, first cycle	Material sciences 7.5 credits, first cycle	Embedded systems II 7.5 credits, second cycle	Safety-critical systems 7.5 credits, second cycle	
Semester 3	Single variable calculus 7.5 credits, first cycle	Applied CAD 7.5 credits, first cycle	Object oriented programming 7.5 credits, first cycle	Physics I 7.5 credits, first cycle	Scientific methods, science and ethics 7.5 credits, first cycle	Autonomous vehicles, 5 credits second cycle	Design of autonomous systems 7.5 credits, second cycle	Programming of dependable embedded systems (DVA494), 7.5 credits, second cycle	Master Thesis work – Dependable systems, 30 credits, second cycle
Semester 4	Electronic systems 7.5 credits, first cycle	Embedded systems programming 7.5 credits, first cycle	Multi variable calculus, 7.5 credits, first cycle	Requirements engineering 7.5 credits, first cycle	Development of safety-critical systems 7.5 credits, first cycle	Robust electronics 10 credits, first cycle	Model based development, 7.5 credits, second cycle	Design of fault-tolerant systems 7.5 credits, second cycle	

Systems engineering related courses

Figure 1. The dependable systems program's course collection.

Semesters 1 & 2 start in autumn and span from September to the start of January, while semesters 3 & 4 start in January and end in early June. During the summer a 10-week period "fifth" semester can be used for various project works, often accredited for 7.5 credits in a relevant subject area. "First cycle" courses are counted as basic courses, while "Second cycle" courses are counted as advanced courses. Often this means that second cycle courses require completion of certain first cycle courses to enroll. This system promotes progression in studies which is a means of increasing students learning (Barrie, 2004).

At the hosting University the subject of "systems engineering" is not recognized as a study subject, partially as it is "to generic", but also due to a lack of alignment with local industry. Rather, "dependable systems" offer a narrower focus more aligned with research initiatives at the University in addition to industrial focus areas and is recognized as a study subject (in fact it is recognized as a technology area but treated like a study subject). The program consists of several courses expected for any "Civilingenjör" program, such as mathematics and physics. The program also offers a broad range of courses to cover a large engineering base in programming, electronics, and more general engineering skills such as control theory and measurement theory. Apart from these courses, specialized courses are offered for dependable systems engineering, including courses for design and development of various complex systems, and specific skills needed to support engineers in this process. One unique aspect of the program is the inclusion of a 30 credits long capstone project course (Farrell et al., 2012) in the last year, where students play roles in an engineering project often with industrial partners or researchers acting as customers.

Staffing the program is challenging but we have managed to achieve it through cross-department collaboration. The teaching ability for the "Civilingenjör" program in dependable systems is satisfied in terms of personnel. The distribution between female and male teachers are higher than average for Swedish Engineering Programs, 29% versus 25% women. 83% of the teachers have a PhD degree or higher (not considering the course assistants, which typically are PhD students). In Sweden, it is seen as beneficial to have teachers with a PhD degree. It is also mandatory (in the long term) for the teachers to have at least 15 credits of pedagogy in higher education. 76% of the teachers in our program have at least 15 credits of pedagogy in higher education.

The program offers 30 new 1st year program slots for students to apply for each year, which is counted as "one class" of students. Most engineering programs at the University are structured around 1-2 "classes" of students to enroll on a yearly basis. Approximately half of them manage to get their degree, which is in line with all other engineering programs in Sweden (Ingenjören, 2021), where many also have some type of delay in the process to get the degree (for a variety of reasons). This program sees more students go on to become PhD students compared to other engineering programs within the department/university. Interestingly, the range of PhD topics among these graduates is large, and there is little overlap between the subjects of the students (e.g., AI, Embedded electronics, Model-Driven Engineering, etc.). The students from the program are also prone to getting hired for positions in critical engineering domains, such as safety or security. Likewise, students are more likely to get hired as managers within a few years on the market compared to other related engineering programs at the University, perhaps indicating their worth in more of a "big picture" view of engineering or inclusion of soft skills. All graduated students have so far been able to find a job or research position in a relevant field after graduation.

Overall, we draw the conclusion that the education program is seen as valuable from an industrial perspective in addition to offering a foundation for continued research. Similarly, the education setup is meeting or exceeding the quality requirements as expected by the university in accordance with the Swedish law.

Systemic barriers for systems engineering education

Taking into consideration the previous chapter of the SE program, we summarize some of the more explicit barriers to offering SE education in the Swedish educational context in this chapter. These barriers are based on our knowledge of the Swedish education system and the experiences of managing a program for several years. Due to this context, some of these barriers might not extend beyond the Swedish system, but we still feel them necessary to discuss as means of feedback for the wider SE community. Each of these points is discussed in isolation, attempting to offer a view from the university perspective, as well as from the student perspective, to highlight the barriers from different angles.

SE is a holistic discipline. SE requires education to include many subjects to capture essential aspects of the system life cycle (INCOSE, 2023). In the program plan we have continuously strived to include a wide base of aspects but decided to provide technical depth in computer science. A consequence of this program structure is the involvement of many different parts of the university organization to provide the necessary teacher competence. This kind of cross-disciplinary and wide collaboration for education is in many ways challenging in terms of internal organization. Any change to the program requires a wide range of stakeholders to be involved, and discussions about the program involves many representatives across the organization. Similarly, in discussions with industrial partners there is often much that is not shared in terms of definitions, assumptions, or use of SE. This balancing act results in a sense of compromise for stakeholders, which is not often appreciated.

From the student perspective, creating a mix of courses necessitates compromising between many subject areas which leads to frustration from students (e.g., why should I learn X when I only care about Y) but also the teaching staff (e.g., students learning “wrong” definitions from field X later observed by staff in field Y). Nonetheless, by both faculty and industry representatives this is seen as a necessary part of a broader SE education. SE courses often benefit from group projects, which can be challenging to perform and create many frustrations among students. While very important, engineering students often have an intrinsic distaste for group projects inherited from their educational past. Nonetheless, we continuously conclude that group work and projects are an essential part of teaching necessary collaborative and communicative skills, also reflected in literature (Bengtsson et al., 2024; Herzog et al., 2018).

SE is about decision-making. In traditional engineering disciplines there is often a focus on “solving problems”. This is reflected in engineering education as well, where often the aim of a course is to construct a solution to a problem. SE, however, is more so about the reasoning and trade-off between choices. Providing adequate education opportunities in this context emphasizes reasoning and analysis and often necessitates more resources when grading a student submission (e.g., a trade-off analysis and report contra well-defined solutions to standard problems). In the Capstone course as an example, the syllabus emphasizes the students need to reason, which results in much documentation to be read but also discussed with students.

Teaching a way of thinking can be very frustrating for students. It is challenging to provide meaningful feedback on a way of thinking and reasoning about system design (Muller & Bonnema, 2013). Students often fall back to asking, “*Is the answer wrong?”*, and often from the perspective of the course it’s not *wrong*, rather the reasoning for *why it’s right* is missing. This causes frustration when in the students’ eyes, they have provided “the right answer”. Addressing this frustration in the framework of higher education is necessary but can often be a process that takes several years to “kick in” for students, sometimes seen as a force of dissuasion for students’ engagement in their own studies (Deslauriers et al., 2019).

Non-tangible aspects of SE. Since SE is in many parts about *thinking* and *reasoning* it might be difficult to directly point to SE in practice (INCOSE, 2023). This difference in positioning is often hard to demonstrate and is often seen as a stark negative compared to other engineering disciplines. We do note, however, that emphasizing these aspects of engineering has allowed us to recruit a new group of students who feel less connected to traditional engineering. This can clearly be observed in presentations for high school students, where there is often a positive surprise for many students when engineering is discussed more in terms of risk management rather than “making solutions”. Of course, the opposite is also true where students might be more disappointed in the perceived "lack of" traditional engineering aspects when put in comparison with other engineering program alternatives.

From a student perspective, the non-tangible aspects are often reflected in the course package having a wide range of courses spanning "soft" and "hard" fields. Engineering students often relate much more to the solution domain compared to the problem domain. STEM subjects in the pre-university studies are heavily slanted towards solving "standard" problems, often in textbooks or common lab assignments. Aspects of design are generally missing, and once students become exposed to more problem-oriented engineering, it feels like moving the wrong way to them. Figure 2 shows one example from a course emphasizing creativity in design (development of safety-critical systems). Instead of addressing a complex system immediately, the students start to reason about the design of an incubator. For simplicity, the design concerns only one parameter first, temperature. They discuss how the system shall work and define hazards and corresponding requirements. The first architecture and the corresponding fault tree (version 1 in Figure 2) cannot meet the requirements. Therefore, they need to refine the architecture and must discuss suitable fault-tolerance techniques such as redundancy and monitors.

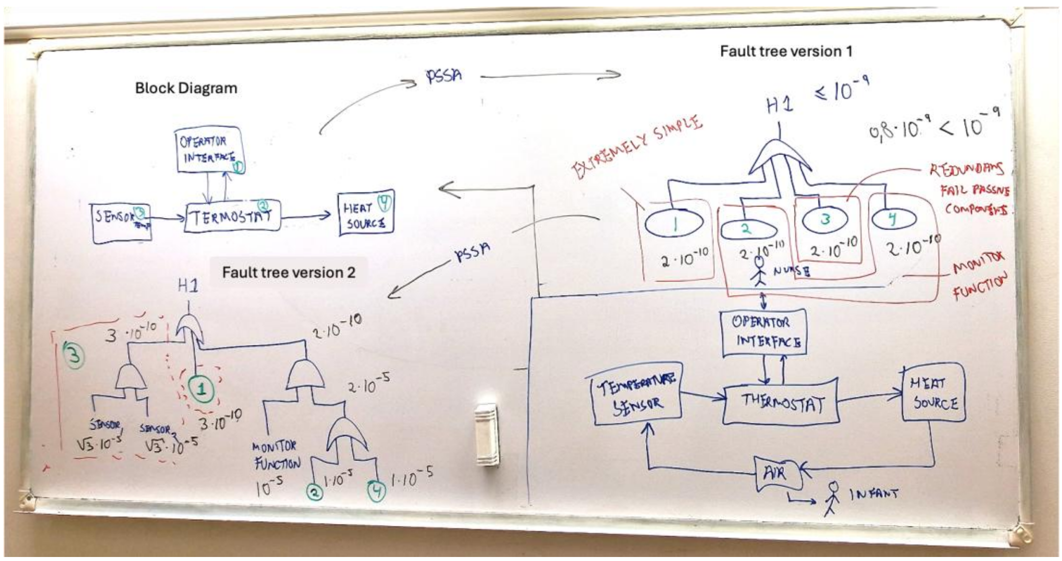

Figure 2. Example of a fault tree exercise given in one of the first courses in the program. The exercise is based on material from the Federal Aviation Administration (2009).

Learning by doing. SE, like many other disciplines, emphasizes a "learning by doing" paradigm. Nonetheless, the "doing" part often cannot be practically integrated into the education until a few years into the program. Therefore, it can feel to some students that they are not sure what they are studying towards until later in the program. Introducing more large-scale collaborative "SE courses" has been tried in earlier years, but then the challenge is making them of enough academic depth to work towards the learning outcomes from the university's mission perspective.

Students sometimes express the opinion that they did not see the value of SE before graduating and working in "reality". One of the more existential criticisms of students in the program is the challenge in understanding the value of SE education through the offered courses. At the same time, alumni often praise the education program and speak highly of the structure and contents. One significant improvement in this regard is the inclusion of industrial guest lectures, study visits, and co-production in several courses from the very start of the program.

Intuitiveness of SE. What is SE? Many of us as researchers cannot provide this answer, and it is a constant debate in popular venues like the INCOSE International Symposium. The same difficulty is also found among students, and explaining or delivering a solid explanation is challenging. It is even more challenging for students to transfer their understanding to potential employees, especially if compared to other specialized subjects such as "robotics", "energy systems", "software engineering", etc. A pragmatic solution has been the inclusion of the keyword "dependable" in education, as that is much more intuitive for students, teachers, and employers.

Students often have a challenging time to understand grading in terms of *how well a design-decision was motivated* rather than *how well a solution was created.* Their experience of grading often directly links with this notion, "a better solution equals a better grade". While often partially true, a common gap in students is the surrounding motivation and rationale. This can lead to students failing parts of a course while not necessarily failing at the work itself. For many students this is perceived as a strict negative, where the evaluation and grading is less "clear cut" and more in terms of presentation.

SE requires time to learn. Providing SE education within a 5-year period is challenging, trying to scope it within 3 years we believe to be next to impossible. While there are programs at a bachelor's level offering systems engineering, for example in the US, we believe those programs suffer the same challenges as 5-year programs and that students are expected to also take a master's degree. The notion of a "system life cycle" entails a lot of things, and from an educational perspective it can be challenging to provide the experience required to grasp the meaning. We try to offer a glimpse into the perspective through offering a two-term long capstone project. The course plan can be seen on Fig.3.

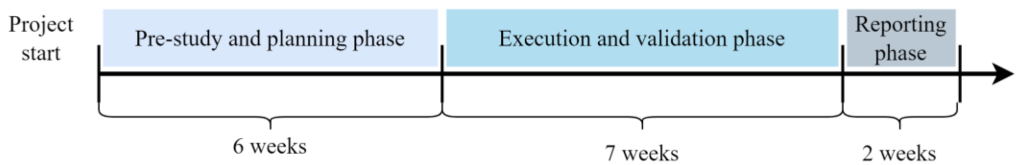

Figure 3. The capstone project outline.

From the students' perspective this means that it takes a long time to grasp the details of what it means to be part of a system's life cycle. The perception of the capstone course is often seen as "eye-opening" to the nuances of collaboration across a larger project. Specifically, working in distinct roles, *necessitating* collaboration among each other to succeed is often very challenging but offers a large learning opportunity. Nonetheless, being the last course before the thesis it takes a long time for students to get the benefits of this course. At the same time, it has been challenging to offer a similar course earlier in the program, something that has been tried as early as the first year.

SE is not widely recognized as a field of study. Given that SE is hard to define, it follows that it is not widely recognized. On a faculty level this is problematic as different subjects need to be included instead of simply "SE". To enable a holistic view of engineering courses "belonging" to different subject areas are more economical to include. Similarly, from the faculty level it makes more sense to open courses for more students to reduce redundancy in teaching and promote more effective resource management. As a result, the student body will study with many kinds of study mates and teachers which might impact their adjustment to the educational system, given differences from course to course.

From a student perspective, it is challenging in their process of being recruited by companies as there is no history or recognition in the name. This can be exaggerated by the fact that courses have course codes or names related to surrounding engineering fields. Students as such might not have a clear idea of "*what field am I really studying in?"*. While it might be possible to properly explain this in the early stages of education, it might still leave a negative feeling for students as they might find it challenging to explain to others what their field of study is.

Reflections. The barriers presented should not be seen as problems that need to be addressed, rather as something to be taken into consideration during program design. There are practical solutions that can alleviate or address these barriers, employed both by us and by others. Instead, these barriers are meant to offer a joint view on the many complexities that goes into creating a university program in Sweden.

Current trends

There is no doubt that systems are becoming more and more complex (this has, in a sense, always been true). Industry trends and new technologies fuel the increase in complexity. New types of hardware architectures such as AI accelerators, embedded graphical processing units, energy-reducing approximate computing units, and diverse computing cores in conjunction with new types of algorithms based on, e.g., machine learning, help solve more complex problems. There is no question that SE is becoming more and more important. However, SE must cope with these new trends and technologies. We briefly present some of the current trends having an impact on the dependable systems program design. It should be noted we have not fully incorporated the trends in our program but will do it in the near future.

When developing dependable systems, it is very important to understand the design space and have complete knowledge about the intended function and behavior for all situations to mitigate unknown unknown faults. Known faults (e.g. random faults) are mitigated through traditional fail-safe design concepts like redundancy and proven reliability while known unknown faults are mitigated through strict development processes. Whereas Model-Based Systems Engineering (MBSE) may help in reducing known unknown faults to an acceptable level (Madni & Sievers, 2018), the real strength comes into play for minimizing the type of faults no one knew could exist due to incomplete knowledge of the functionality. These types of faults (unknown unknowns) are more prevalent in systems using new technology, for example machine learning-based functions. Many of these functions are formed using input training data. Thus, the design is based on input data, which in turn needs to be fully controlled and understood. To support this process, scenario modeling of AI-based systems may help. The scenarios are built upon initial conditions and a timeline of significant events. Three different levels of scenarios may be used: operational, conceptual, and executable scenarios. Scenario modeling supports some objectives for trustworthiness analysis, e.g., requirements in defining and documenting the concept of operations for AI-based systems (Gupta and Durak, 2024).

The guideline document SAE ARP4761A includes processes for system safety assessment and analysis. The document is aimed at conducting the safety assessment process on civil aircraft, systems, and equipment. In the latest issue, Issue A, released in December 2023, a new analysis method, Model-Based Safety Analysis (MBSA), was introduced. MBSA shall not be mixed with MBSE; they share many things but have different goals and ways of working. Traditional safety assessment methods such as fault-tree analysis (FTA), Markov analysis, or dependency diagrams, can be replaced with MBSA, while other analysis methods such as common mode analysis can be supported by the method (SAE ARP4761A, 2023). FTA will, however, be the dominating safety analysis method in many years to come due to its ease of use in discussions with customers and certification authorities. With MBSA, communication between system and system safety engineers is performed through models. The safety analysis is performed through Failure Propagation Models (FPMs). FPMs help in understanding system behavior, and thus, very complex functions can be addressed. MBSA is not limited to being used in the avionics domain but may be used for other domains as well.

Educational principles

In the previous section, we mentioned some trends and how SE can help solve some of the obstacles. In this section we relate the trends to education. Many educational trends are connected to the INCOSE vision - sustainability, digital transformation, sociotechnical systems, heterogenous systems, cybersecurity (trusted systems), and autonomous systems (INCOSE, 2022). While we address some of these trends already in our current program it took some time before we introduced cybersecurity. In fact, members from our program's Industry Council asked to bring it into our program a long time ago but we struggled to make space for it (another course had to be removed and that was not an easy task!). Similarly, many of the "larger" aspects of the vision are slowly integrated into the wider educational system in Sweden, and as a result, in some way or another catered to in education without additional intervention. Nonetheless, we emphasize *model-based trends* expected to have a large impact on our program going forward, to address increasing complexity in engineered systems in addition to challenges in collaboration and communication.

By considering the experiences gained so far, and the vision portrayed for the future of SE by INCOSE, we want to provide a set of principles to drive educational management for our program going forward. We note that these principles are in part driven and constrained by the Swedish educational system.

Principle 1: Students ownership of their own learning. Students who feel ownership of their project tend to have more intrinsic motivation towards their own learning, something supported by pedagogical literature (Xerri et al., 2018). We have found it very successful to let students manage their own projects, while we act as stakeholders and project owners on the faculty side. Even more successful is when these projects are directly targeted towards industry, where local industry can act as the customers. In this regard, the students are "left in charge" of their own learning, offering courses as opportunities for innovation and creative thinking. There is a balance between freedom and strictness toward expected learning outcomes, but we believe achieving a successful balance is manageable with the introduction of continuous feedback from teachers, also supported by pedagogical science (Barrie, 2004). Continuous feedback on students' progression in a course, with possibilities to address concerns throughout, is seen as positive. In this course layout continuous feedback is provided by domain experts each week, with a stricter review of the project at 3 distinct phases (end of phases). This results in continuous feedback enabling students to drive the project without feeling "lost" in their assignments. To further support the feeling of ownership, the University offers support for students as seen in Fig. 4 to be self-driving in their studies.

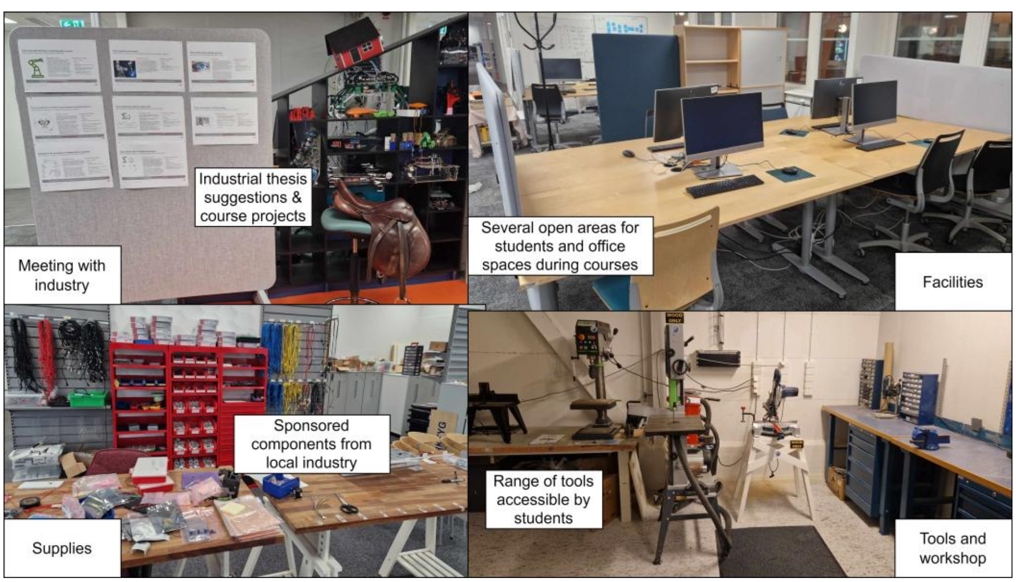

Figure 4. University setting for engineering courses and projects.

Principle 2: Supporting the T-shaped engineer. A T-shaped engineer has deep knowledge in key disciplines and broad knowledge in other fields including soft skills. We do not encourage to suggest a golden solid group of SE courses to be used by every university. Instead, we believe that a broad collection of STEM courses should be created in relation to the expertise available at each University. Attaching SE and systems thinking to something tangible like safety can greatly improve the cognitive ability to reason practically for students. We have found it very successful to let students play roles in collaborative projects. Not only do students take ownership of the projects but also specific aspects of the project that enable students to "dig deeper" into specific areas of interest. This is also a good way to simulate the collaborative aspects in industrial settings between sets of different stakeholders. Other courses include juridical, ethical and human factors to broaden the student's skills in related non-technical subjects.

Principle 3: Industrial presence in education. There is no doubt industrial interaction is very important. We strongly suggest collaboration with industry to ensure:

- that the university educates students attractive for the industry in the future.
- that the program teaches knowledge needed and asked by the industry.
- that current and future trends within the relevant industries are not missing.
- increased collaboration between the parties, both regarding education and research.

To ensure the above we have created an Industry Council for the program that meets 1-2 times per year or more often when a revision of the program is ongoing. We also investigated the industry collaboration in all courses in the program. 50 percent of the courses had some kind of collaboration with industry partners (guest lectures, study visits, project work, alumni days, mentor programs, specific days for master thesis discussions etc.) This level of industrial integration is highly appreciated by the student body.

Principle 4: Connection with research and future technology. To support a research perspective much of the coursework is managed and operated by researchers, where it is encouraged to support the inclusion of recent and relevant research results. We believe a similar principle could support other programs as well, for example SE educational programs that include AI in their education are advised to include teaching trustworthiness and explainability. To support some of the objectives for these conditions, scenario modeling of AI-based systems may help. To support the complexity and increase in safety-critical systems, MBSA has been proposed and included in the guidance material for development of aircraft and avionics systems. For the same reason, we plan to bring in MBSA to one of our advanced courses in the Dependable Systems Program (we have not done that yet). We will however not abandon the traditional analysis methods like fault-tree analysis, but instead we suggest using them together. Model-based approaches are becoming more and more dominant in several relevant industries. One direct consequence is the increased emphasis on MBSE, emphasizing general purpose modelling languages like SysML during coursework. At the same time, specific modelling activities are also becoming more prevalent like 3D modelling and simulation.

Principle 5: Communication as a core skill. A systems engineer requires the capability to interact and communicate with a wide range of stakeholders. We emphasize communication as a core principle of our curriculum and promote the use of various collaborative group projects. To avoid pedagogical pitfalls of group projects such as a feeling of uneven contribution among students or lack of individual acknowledgment in grading, we utilize role-based projects. We also promote several different means of communication, from project posters to project presentations among other students or the wider public. Another way to promote students' communication is to let student's "pitch" their projects during projects. In the facilities for the Capstone project, we regularly invite industrial partners to interact with students and one way to kickstart this interaction is with student project posters. A project poster from 2024 (group of 5 students) is seen in Fig. 5.

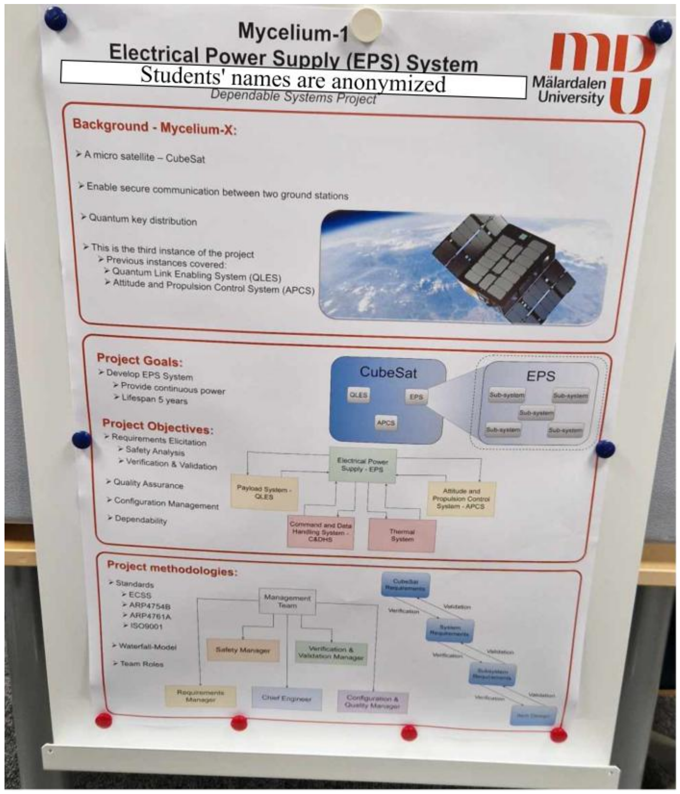

Figure 5. Capstone project poster example from 2024.

We note that one of the projects has industry as customers, with factory visits and regular meetings. Through interaction with industry, students get a larger context for their studies, while also acting as a useful networking opportunity. At the same time, the other project is a research project, offering closer collaboration with university researchers.

Summary. These principles of education have been developed through the continued quality assurance of the educational program through interaction with industry, researchers, students, and faculty. We believe these principles are a sound set of guiding principles to promote quality SE education while supporting continued development and adaptation based on practice and research.

Conclusion

In this article we provide experiences from managing a systems engineering program in the Swedish educational system. We discuss the nuances of teaching systems engineering in our context and describe the general principles behind the program. With the program as a foundation, we discuss the challenges in providing systems engineering education, and how the multi-disciplinary scope creates practical and foundational challenges. We provide our view as program managers, from industrial feedback, and student evaluations as a guide during the discussion of this paper. We end the paper by presenting several take-aways for future education in systems engineering, namely five principles to drive education going forward. The principles are *students' ownership of their own learning*, *supporting the T-shaped engineer*, *Industrial presence in engineering*, *connection with research and future technology*, and *communication as a core skill*.

Future work. In the future, we expect to continue shaping the program to match the needs of industry and changes in the technical landscape. It would be useful to align with other educational programs in other parts of the world to find common challenges and common solutions. Ideally, educational systems across the world could align with the INCOSE vision for the future of systems engineering and provide necessary arenas to train the future systems engineers.

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Biography

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