Systems-of-Systems Engineering Online Education: An Experience Report

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***Abstract*—Online education is changing how teaching is done at universities and provides new opportunities to reach out to practitioners. In this paper, the development of an online course in systems-of-systems engineering is presented, as well as results from the first instance of the course. The paper describes how the course was designed; how it was produced; and experiences from giving it. Challenges with online education in the systems engineering subjects are also highlighted.**

Keywords—system-of-systems, systems engineering, systems thinking, education, online teaching.

I. Introduction

Systems-of-systems (SoS) is a term that denotes a situation where independent systems collaborate to provide a capability that they cannot provide by themselves. This type of systems is becoming increasingly common as the digital transformation of society proceeds. By participating in an SoS, an individual constituent system (CS) gets access to information from other CS which it cannot access itself, or which would be prohibitively expensive to collect. The application of SoS is spreading from its initial use in primarily defense, to domains such as transportation, emergency response, manufacturing, mining, construction, and health [1].

With the increasing importance of SoS, it also becomes critical to better understand how to perform SoS engineering (SoSE) through research endeavors, and to spread that knowledge to practitioners through education. INCOSE, in its Vision 2025 [2], points out both the importance of SoSE in the future landscape of systems engineering (SE), and the need for education, not the least lifelong learning that allows existing practitioners to get access to SoSE techniques.

A concept for lifelong learning that has become increasingly common in recent years is online education, which has been made popular by the Massive Open Online Courses (MOOC) provided by university spin-offs like Coursera, edX, and Udacity. These MOOCs can handle extremely large numbers of students and are based on extensive automation to be scalable without increasing the teaching effort. However, online education is also increasingly used by traditional universities, where interaction with teachers is offered to allow deeper discussions beyond what automation can handle. The technology for online education has matured, and there are various well-proven learning management systems (LMS) available.

With this in mind, Mälardalen University (MDH) in Sweden started in 2018 to develop a course in SoSE that could serve both advanced level university students and the continuous education of practitioners. Since there are relatively few students with an interest in SoSE at a single university, and practitioners are also geographically dispersed, the format of an online course appeared suitable to attract a sufficiently large number of students from a broader geographical area to motivate the course development effort.

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The development of the SoSE course at MDH is part of a larger effort in increasing the university's range of online courses, and this meant both that there were some common resources to support development, but also some constraints on the design of the course. One of those constraints was that the course should formally be a normal university course, and both give official credits and live up to all regulations pertaining to university courses. This meant, among other things, that a totally open MOOC was not an option.

To our knowledge, there are few prior examples of SoSE online courses, and the contribution of this paper is to describe both the resulting course, and the experiences of developing and giving it.

The remainder of the paper is structured as follows: In the next section, the development of the course is presented. Section III describes the delivery of the first instance of the course, and Section IV discusses some experiences and challenges related to this type of education. Section V presents related work, and the final section summarizes the conclusions and provides some ideas for future work on the topic.

II. Course Development

In this section, the development of the course prior to the first instance is described. This is done with a basis in the constraints set by the environment and the learning objectives identified; it then proceeds with the design of the course, and the production of the various artifacts, such as lecture material, literature, exercises, and the use of the LMS.

A. Constraints

As mentioned in the introduction, the university environment enforced several constraints on the course. The first was the size of the course. Within the umbrella project for developing multiple online courses, it had been decided to have a standard size corresponding to 2.5 ECTS (European Credit Transfer System) credits. In ECTS, one full year equals 60 credits, so 2.5 credits should correspond to around 70 h of total effort for the students.

The course should give university credits, and it was therefore not an option to create a MOOC on one of the commercial platforms. Instead, the course was conceived as a normal university course, with the only difference that it should be delivered over the Internet instead of in a classroom. The normal national university admission system was to be used, and the course was classified as being on the Advanced (MSc) level, meaning that prior studies of at least the equivalent of a BSc in engineering was a prerequisite.

It was also an explicit objective of MDH to make the new online courses available internationally. Therefore, the course was developed completely in English. Due to regulations, participation is free for EU residents as well as citizens of a few associated European countries, whereas participants from other countries are required to pay a fee of around €500.

MDH has standardized on the Canvas LMS, which was, therefore, a given choice for the course, and a video distribution platform was also provided by the university.

B. Learning objectives

Due to the relatively limited size of the course, the overall purpose was set to give an overview of concepts relevant to SoSE rather than providing more practical experiences. The following learning objectives were formulated:

1. Present key principles of systems theory and SoS.
2. Describe building blocks and tools used in SoSE.
3. Explain analysis methods for key SoS characteristics.

The objectives are also the foundation for the examination.

C. Design choices

Several overall design choices had to be made during course development. A first one concerned the pace of the course. Since one target group was practitioners, the pace had to be limited to allow combining studies with work, and it was decided to settle for a 25% pace, i.e., a total student effort of around 10 hours per week, for 7 weeks. The course was divided into seven main modules, i.e., one per week. Each module was designed to consist of lectures; literature for reading; and some non-graded exercises to check the student's understanding.

The examination was divided into three smaller written assignments each corresponding to one of the learning objectives. To ensure a fair grading, the deadlines for assignments were fixed, and this was also intended to encourage the participants to study at an even pace. Apart from these deadlines, the participants were given full flexibility regarding when to study.

D. Content

The contents of the seven modules of the course were:

1) Characteristics. Basic definitions of SoS, including Maier's characteristics [3] and the Maier-Dahmann archetypes [4]. Also introduced a number of examples of SoS applications.

2) Systems thinking and systems engineering. Theoretical foundations from systems science and cybernetics, including general characteristics of systems, hierarchies and system dynamics. Also introduced key elements of SE for integrated systems, and clarified how SoSE differs from traditional SE.

3) Engineering methods and tools. Modeling techniques such as conceptual modeling in UML/SysML and dynamic modeling and simulation, including agent-based simulations. Also discussed cross-organizational collaboration and quality assurance.

4) Architecture. Architecture descriptions according to ISO42010, and a set of viewpoints suitable for SoS. Review of architecture frameworks such as UAF, and principles of service-oriented architecture. Design patterns for CS architecture to enhance adaptability to a particular SoS.

5) Interoperability and information representation. Different interoperability levels according to [5], and introduction of semantic web techniques such as linked data and ontologies for dealing with the different interoperability levels [6]. The role of world models and their contents in higher levels of interoperability.

6) Business models and incentives. The structure of a business model using the Business Model Canvas [7], and the use of game theory [8] to explain emergent behavior caused by incentives. Service level agreements as a tool for reducing business risks and uncertainties.

7) Trustworthiness. Approaches to risk analysis, and its application to safety, security, and privacy.

Systems thinking was used throughout the course as a foundation, and many parts were explained using it, such as the analysis of trustworthiness in the last module.

An important aspect of university education is its foundation in science and the need to critically assess knowledge. This, in combination with a desire to make a course that could attract participants from many areas of society, led to a need to critically review some of the "best practices" in SE and SoSE as presented by e.g. INCOSE. Many of those practices have their roots in the defense sector, in particular in the US, and are not always the best choices under other circumstances. Therefore, inspiration to the content was also sought outside the limited sphere of the SoSE community.

E. Lectures

Each module consisted of 4-6 video lectures that were pre-recorded. There was also an introduction video to the course, and a summary at the end, giving a total of 39 videos and a total duration of 10h 36 min (i.e., about 1.5 h per module). The duration of the videos varied from less than 3 min to around 32 min, with an average of 16 min. The lectures were based on Microsoft Powerpoint presentations, that were newly developed for the course. It was considered essential to include a live image ("talking head") of the presenter in the videos to create a feeling of presence and help the students build a kind of personal relation to the teacher.

Several different tools for video production were considered, but in the end, it was decided to record videos directly in Powerpoint since this turned out to be very convenient. This feature allows to integrate an image of the presenter in the corner of the slide, and synchronization of video, animations in the slides, and voice is also automatic. Once recording is completed, a video file can be exported from Powerpoint, and uploaded to the video content delivery system. The lecture slides were also made available for download through the LMS.

Experiences from prior online courses at MDH indicated that the quality of video recording of the lecturer is secondary, but sound quality is essential. Therefore, a professional microphone and mixer was used for sound, whereas a standard webcam was used for the presenter image. No special studio was needed, but the videos were recorded in a normal office with just a neutral background behind the presenter. Fig. 1 gives an example of what the videos looked like.

F. Literature

Due to the urge to give a broad view on SoSE, and critically include material from many sources, it was not possibly to use any existing textbooks for the course. Instead, it was decided to use a set of, in total, 15 research papers, i.e. 2-3 per module. These mandatory papers were a complement to the lectures and went a bit deeper into some of the topics, but without fully covering the total contents. The lectures thus remained the primary source of information in the course.

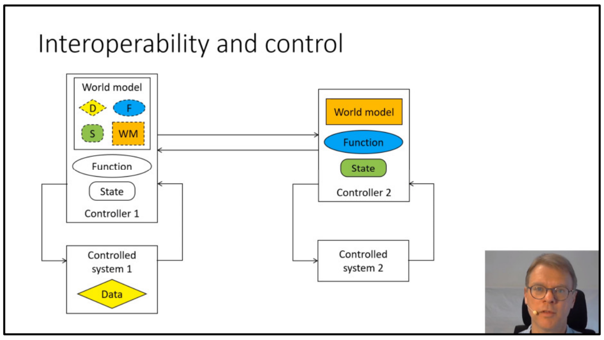

Fig. 1. An example from a video recording of a lecture in Module 5, showing the author at the bottom right.

In addition to these mandatory papers, a longer list of about 100 references was provided, as a service for students wishing to dig deeper into a specific topic.

G. *Exercises*

To allow the students to test their understanding of the lectures and papers, some quiz questions were included in each module. These were non-mandatory and automatically corrected by the LMS. In total, there were 50 questions, with a variation between four and 11 per module. The students could redo the quizzes as often as they liked.

In Module 3, there was an additional hands-on exercise on system dynamics simulation, where a small system was to be modelled using a stock-and-flow diagram in the online tool Insight Maker [9]. The exercise consisted of a tutorial where the students were shown step by step how to build the basic model in the tool, and then they were given a few small questions that required extensions to the model. This exercise was also not mandatory, and answers were not reviewed by the teacher unless asked for by the students.

H. *Examination*

As mentioned in Section II.C above, there were three mandatory assignments covering the learning objectives. The assignments were typically providing an SoS application example, and then asking the students to write a two-page text that covered a number of topics listed in the assignment. Each exercise was graded as Pass or Fail, and if a student failed on the first attempt, one more chance was given with another firm deadline. The whole course was also graded Pass or Fail, and to Pass it was required to Pass on all three assignments.

I. *Interaction*

A major challenge in online teaching with pre-recorded lectures is to establish an interaction with the students. To remedy this, the course had a discussion forum in the LMS, where students were encouraged to bring up topics, and also respond to each other's questions. Every week there were one or two tuition meetings through video conferencing, where the teacher was present to answer questions live, and anyone interested could join. Further, the LMS contained a messaging system, and the students had access to the e-mail address of the main instructor and were encouraged to get in touch.

It is also important to capture feedback from the students on the quality of the course, and for this reason MDH has a standardized course evaluation at the end of every course. In this course, it was desirable to get faster and more detailed feedback, and therefore after each module the students were asked to rate on a 1-5 Likert scale how they viewed the quality of the lectures, papers, and exercises of that module. They could also supply free text comments.

The LMS also provided various kinds of feedback, that could be used to review the progress of students and hence indirectly how well the course worked.

III. First Course Instance Delivery

The first instance of the course was given in September and October 2019. In this section, it is described how that instance was prepared and conducted.

A. *Marketing*

A first step in running a course is to attract students. In this case, the course was announced using traditional channels such as university web pages, and through the national university admission system. In addition, the umbrella project for course development did some marketing for the group of online courses, such as contacting larger companies that could be interested in encouraging employees to participate. Also, personal channels such as LinkedIn, mailing lists such as INCOSE Sweden chapter, and company and university contacts were used. However, marketing for this first instance was primarily towards a Swedish audience.

B. *Admission*

The students applied to the course through the national university admission system, which is web based. In this system, they can apply for several alternative courses and programs, which they rank in their order of interest. The normal schedule is that admission to courses in the fall semester closes in mid-April, but with an audience that includes practitioners, this long foresight was considered unrealistic, and therefore the admission for this course was kept open right until the start in September. All applications are manually reviewed by administrative staff to ensure that the qualifications are met.

In this instance, a total of 97 persons applied through the admission system, and 64 of them were considered as qualified. Of these, 16 withdrew their applications, and since very few of them had this course as their top choice, it can be presumed that most of them withdrew since they got accepted to a higher-ranking alternative. In addition to the remaining 48 students, three PhD students from MDH enrolled through an internal procedure, resulting in a total of 51 students initially.

Due to privacy concerns, few demographic details were collected, but the birth date, names, and telephone numbers were available. The birth year varied from 1958 to 1995, with an average of 1982 (i.e., age around 37). A typical student who continues to university directly after school would be around 22-24 years old when attending MSc courses. This indicates that there were probably a fair number of practitioners taking the course. Individual contacts during the course also confirmed this, and it was estimated that at least 2/3 of the students were practitioners. Based on the names, it is estimated that 15-20% of the students were women. The telephone numbers showed that even though a few foreign students did get admitted, in the end only students living in Sweden started the course.

C. *During course*

A couple of weeks before the start of the course, a welcome letter was emailed to the students with instructions how to get started. During the following weeks, the same letter

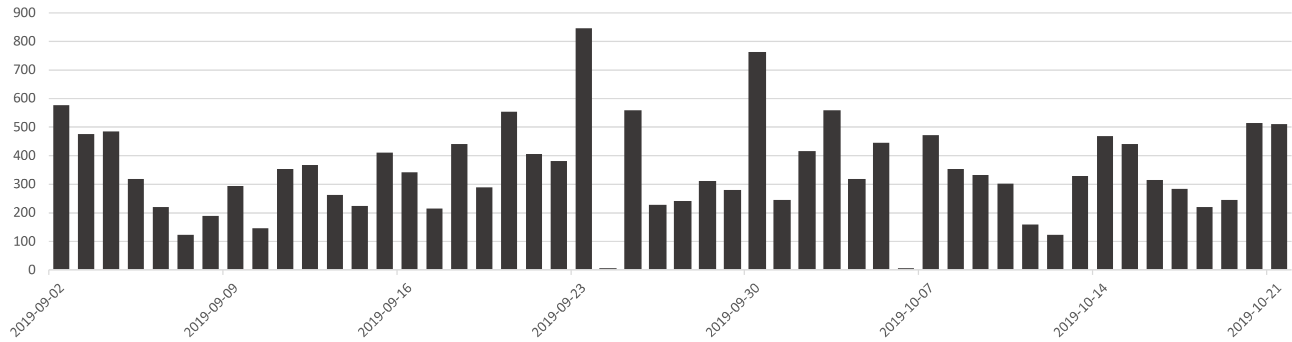

Fig. 2. Web page views per day as recorded by the LMS.

was also sent out to late admissions, as soon as they showed up in the admission system. The instructions were an introductory video with tips and tricks, and some formal rules.

Once the course started, the number of students gradually diminished. Most of the dropouts occurred early, consisting of students not starting at all or making only a small initial effort. 30 of the 51 students handed in the first written assignment, and out of these, 26 eventually completed the course. Although dropouts are never a good thing, this pattern was still acceptable since it involved a small wasted effort both for the students themselves and the teachers.

A concern was interactions with the students. The scheduled tuition meetings had very few participants and did not provide much value. The discussion forum was very quiet initially, but as the course proceeded some questions were getting asked, especially related to the examination. In addition, there was a steady stream of e-mails with questions from students, often regarding practical issues.

Fig. 2 shows the course activity per day between the official start and end, as measured by the number of web page views recorded by the LMS. Many of the higher peaks coincide with the deadlines for examination.

D. Examination

As mentioned above, there were three written assignments, with each response limited to two pages of free text. They were all described as a short scenario, and a set of concepts that the students were to discuss. The scenarios and concepts were as follows:

1. *AirBnB as an SoS*. Is this an SoS? Which archetype is most appropriate? What CS, constellations, mediators are involved? What are the emergent properties and capabilities?
2. *Tool sharing in an ancient small town using a billboard*. What architectural viewpoints and patterns can describe this SoS? Principles of service-oriented architecture? Possibility to simulate using agent based and system dynamics? Important quality characteristics?
3. *Autonomous and remote vehicle control*. Information exchange at different interoperability levels? Business model? Need for service-level agreements? Operational risks and causes?

The second assignment stood out a bit, since it did not involve a modern IT-based scenario, but it was chosen to make the students reflect on some of the similarities between human collaboration and SoS.

All assignments were reviewed manually by the examiner, and individual comments were submitted. Almost half the students were required to revise their first assignment, and a bit less for the second and third (probably since the first attempt established the required quality level). They were given one week to submit the revisions.

The due dates for assignments are quite visible in Fig. 2. Sept. 23 was the initial deadline for assignment 1, and hence Sept. 30 was the due date for revisions. Oct. 6 was the deadline for assignment 2, and Oct. 21 for assignment 3.

The written assignments were checked for plagiarism using an automated system, but no issues were detected.

E. Course evaluation

As mentioned above, the course evaluation consisted of both short surveys after each module and a larger survey at the end of the course, and both types were anonymous and consisted of ratings and free text. Unfortunately, the incentives for submitting the evaluations are not very strong, and hence the response rate was low. Nevertheless, apart from minor details in individual lectures and quizzes, the course was highly appreciated, both in terms of content and delivery.

IV. Discussion

This section discusses some experiences and challenges from developing and delivering the first instance of the course.

A. Design

Designing an online course presents some challenges, and one of the greatest is the lack of information about the students, and the difficulty to adapt during the course. In a normal campus-based course with typical undergraduate or graduate students, the population is fairly homogeneous with similar background knowledge. Here, the group was extremely diverse, ranging from students with no work experience up to systems engineering practitioners with 30 years of experience. For the newcomers to the field, some background to systems engineering was necessary, but for the experienced it was desirable to come to SoSE quite soon. The solution was to have this introductory material on a high level and with a focus on systems theory principles, since this is also not so well-known for all systems engineers.

The choice to use a traditional lecture-based set-up was in some sense a low-risk strategy, and it was also a consequence of the number of available course hours. If a larger course had been possible, it would have been interesting to experiment with other learning strategies, such as problem-based learning, and including more hands-on lab exercises.

B. Production

The main effort in preparing the course was related to the lectures, mainly due to the fact that the course was developed from scratch, and to the urge to go beyond the standard sources to ensure a solid scientific foundation. The overall content was quite clear from the beginning, but the details took over a year to develop, and in the process, several hundred research papers were considered. This work also led to insights in SoSE, that inspired new research publications, e.g. [10][11][12].

After doing some trial recordings to test out technology and procedure, it became clear that to get a good flow in the presentations, a written manuscript was needed. This was particularly apparent when using slides mainly based on graphics, since problems with finding a good explanation or finding the right words are much more disturbing in a video than in a live lecture. It also emerged that using animations, such as stepping through a bullet list instead of showing the whole list, was more important in the videos than in live presentations, and the manuscripts also needed to include instructions on when to trigger the next animation. All this resulted in a substantial effort in preparation of manuscripts once the actual slides were ready.

When the manuscripts were completed, the video production was very smooth using Powerpoint as discussed in Section II.E. A big benefit of this approach is also that it is possible to make changes with a small effort. For instance, it is possible to re-record a single slide without touching the rest of the content, or to change the graphics (e.g. to correct a spelling error) without re-recording at all. The total effort spent on actual recording was about 2-3 times the duration of the video, so in total 20-30 h. Recording requires some concentration, so about 1 h of video is the maximum per day to reach sufficient quality.

The quizzes appear to have been appreciated by the students, but it was somewhat difficult to come up with suitable questions that lend themselves to automatic correction. Many of the more interesting issues in SoSE do not have clear and simple answers but require a discussion or contextualization. In this sense, the examination assignments were easier to deal with, since they required free text replies. On the other hand, those assignments were based on application examples, and it was tricky to find good examples that could be described very briefly.

The system dynamics simulation exercise using Insight Maker was a bit of an experiment and was therefore made voluntary. An explicit question about this exercise was posed in the post-course evaluation, but due to the low response rate it is difficult to know how it was perceived.

The LMS did not provide any major difficulties but turned out to be very mature and easy to use and manage.

C. Delivery

The delivery of an online course is quite different from that of a campus-based one, since lectures are prepared in advance. The main effort here is instead in reviewing the written assignments, and this is also the main mechanism for getting an understanding of the students' progress. Apart from this, the course responsible mainly needs to be available to respond to questions. We believe that responsiveness is a key to how students perceive the course, and have strived to give immediate responses to communication, and give feedback on written assignments within one or two days.

An unexpected difficulty was that some companies have severe restrictions on what software can be used on their computers. Luckily, it was possible to bypass this by e.g. connecting to video conferences using dial-in phone numbers.

Although this course had a reasonably high success rate compared to other online courses, it is still relevant to consider ways of improving this even further. In particular, the needs of practitioners working in parallel to their studies need to be acknowledged. For future instances, we are therefore considering making the course even more flexible, with continuous admission and letting the students set their own deadlines. However, there is a risk that flexibility removes the necessary pressure that some students need to progress.

It is worth noting that there is a conflict of interest among the involved partners. For the students, the main motivation is to learn, and the practitioner students seem to care less about the formal credits. However, for the university, the funding is based on how many credits are earned by the students, and hence a poor outcome will result in less funding, and hence less possibility to develop courses for lifelong learning. Possibly, employers need to play a more active role in this and ensure that their employees are given sufficient time and also motivation for completing the courses.

D. Interaction

Among the relatively few disappointments in the course was the low level of interaction with students. This is a well-known issue for online courses in general, but we did try to give students the opportunity through various feedback mechanisms, forums, and tuition. However, one should bear in mind that interactions with many students in campus-based courses is also limited, and it is frequently a small group of students that engage in discussions whereas others are mostly passive. Having less requirements on interaction improves the flexibility and can thus contribute to reducing dropout rate. The interaction should thus not be considered a goal in itself, but rather one of several mechanisms that can be used to reach learning objectives.

Nevertheless, we have seen it as important to at least have continuous interaction from the instructors to the students, e.g. by making announcements at least weekly, since this provides both a reminder about the course and an invitation to dialogue.

V. Related Work

In this section, some of the related work is discussed, although space does not permit a more systematic review. The first part describes previous work related to SE and SoSE education, and the second provides some insights from online education in general.

A. SE and SoSE education

A number of papers have been written that discuss the design and content of SE education. However, many of these pre-date SoSE, and are based on a classroom setting. An example is [13] which discusses a graduate program curriculum for SE with a focus on lifecycle processes and indicates that it has been implemented for online teaching at several US universities. However, it does not address SoSE.

Kasser [14] apply SE to the design of an SE courseware, with an emphasis on the requirements. It was a source of inspiration for the process of course development, but its scope is different from our course.

A recent publication, which appeared after the development of our course, addresses a MOOC for SE [15]. This course has attracted more than 10,000 learners, although only about 5% completed the course. It is given in French, and hence less accessible for a broader international community. The course is motivated by the increasing use of connected embedded systems, which is a notion related to SoS, but the course does not appear to leverage the current state of SoSE research. Industrial case studies form an integral part of the course.

One of the few papers discussing SoSE education is [16], which describes a one-year on-campus program tailored for the US Navy. Many of the elements are similar to our course, such as traditional SE; systems thinking; complexity; and SoSE specific concerns. They also emphasize case study learning.

B. Online education design

The design of online courses differs from development of traditional campus-based courses, and there is a growing body of research on pedagogics for distance education.

A common theme in online education, and in particular MOOCs, as witnessed in the case of SE [15], is the high drop-out rate, which is also not appearing to improve over time [17]. The same study shows that MOOC students tend to come from affluent countries, and that the MOOC industry is transforming away from its initial open business model and starting to act as a support organization for universities.

The reasons for dropouts is discussed more in detail in [18], and they compare two instances of the same course where the students had tutor support in one of them and no support in the other. The completion rate increased among the supported students, but those students did not participate so much in tutoring, which makes the results hard to interpret.

For a course like ours, the main material is the video recordings, and empirical data on how to make videos that engage students is provided in [19]. The recommendations include videos shorter than 6 min; showing the instructor's head in the video; filming in informal settings; including motion and visual flow. This is confirmed by [20], who indicate that the video length should be below 15 min.

VI. CONCLUSIONS

This paper presents experiences from one of the first online courses in SoSE, developed and given at Mälardalen University in Sweden. The course consisted of 2.5 ECTS credits and was delivered through video lectures; literature consisting of selected papers; and exercises, with the examination consisting of three written assignments. The first instance in the fall of 2019 had around 50 students, mainly from industry, and about half of them completed the course. Some of the major challenges included how to let practitioners combine studies with work, and how to improve student interaction. Due to demand, an extra instance is given in the late spring of 2020, and a third instance in the fall of 2020.

For future work, there are plans to make the delivery of the course even more flexible, with a first implementation in the fall of 2020, although this is a challenge under somewhat rigid university regulations. The course material will also be extended and repackaged for use in other settings. As an example, a shorter version has already been given as a classroom lecture for SE experts in an aerospace company.

We are also looking into opportunities to collaborate with other universities internationally, to make the course accessible to them as part of their master's program. In this way, smaller universities in different countries can offer a broader range of courses to their students.

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