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Reinforcing Learning in an Engineering Master's Degree Program: The Relevance of Research Training*

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Master students at our institute were graduating without acceptable research proficiency. We intervened by shifting our research training from teaching-centred to student-centred, and from research-related subject content to research-related processes. We performed a mixed methods study aimed to confirm there was improved research proficiency without a negative trade-off for our students' engineering skills. Results indicated improvements to research proficiency, which our students were able to transfer to engineering-related learning activities to increase their ability to achieve engineering synthesis. This outcome was potentially supported by our courses including several perspectives on scientific knowledge production. This implies that research training, rather than having a negative effect on engineering skills, can be helpful in learning diametrically opposing aspects of thinking required by current engineering. As engineering education evolves towards more cross-disciplinary cooperation, this implies the need to pursue the increased opportunities for students to learn about different perspectives on knowledge production.

Keywords: engineering education; master's education; science education; research-teaching nexus

1. Introduction

Institutes within the Swedish higher educational system are required by regulation to provide research training at the master's level [1]. How this subject is taught is mostly decided at the institutional level. At our institute, traditional teacher-led and content-focused research training did not achieve acceptable results. Some students graduated with little proficiency in research, and few synergies with other parts of the curriculum were observed. As with many other engineering programs demand from firms and the opening up of new career paths mean that we are currently being tasked with fostering new skills, such as cultural awareness, sustainability, innovativeness and entrepreneurship [2, 3]. Extending the time spent on the subject was thus not an option, since our engineering curricula are already stretched beyond their limits. New student-centred teaching practices, such as inquiry-based learning, have been suggested as solutions to this dilemma [2]. Conceptually related, *inductive teaching and learning* approaches [4, 5] are at times equated with *conceptual*, *epistemic*, *social* and *procedural* aspects of research in learning activities [6].

Unfortunately, the situation is complicated by the fact that the inclusion of research training in engineering curricula has been historically contested. That research is synergetic to learning is only supported by weak evidence [7], and an emphasis on engineering science implies less time spent on practical skills [8]. The popular view of science as providing unambiguous facts might also be problematic: if engineering is posed as an applied science it might result in risky expectations that even complex, highly critical systems can always be reduced to a set of assessable facts [9]. While we wanted to improve our students' research proficiency, we had to acknowledge that research training could have powerful implications for our students' understanding of knowledge production and engineering skills. Using inquiry-based learning might aggravate the situation, since an abstract and often unfamiliar subject such as research training is not optimally matched to this approach [4]. The result could be that our students would, regardless of their ability to independently conduct research, gravitate towards forms of scientific knowledge production that would impair their ability to perform engineering design.

This paper describes the study of our intervention into the research training in one of our engineering master's programs. This intervention shifted the teaching from teaching-centred to student-centred, and the emphasis from research-related subject content to research-related processes, skills and worldviews. Our interest was to understand any causal relationships between this shift and improvements to research proficiency; and whether these improvements would come with a negative trade-off to our students' engineering skills. This involved identifying the nature of any improvements and relating it to fine-grained elements of research and learning. The novelty of this research focus is twofold. Firstly, the graduate level itself is under-

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studied in regard to the relationship between research and teaching [10], and engineering education [11, 12]. Secondly, studies of the research training provided by graduate engineering programs are scarce, even though research training could be seen as the core of the graduate engineering degree [13].

The next two subsections provide a basis for the paper by describing the research discourse closest to the domain of study and the conceptual framework adopted for the study. The background and research design of the study are described in the subsequent section. A mixed methods design was used, primarily due to the many confounding variables that had to be controlled upon identifying a shift in the student population. The results are then presented, analysed and discussed in regard to learning and future implications. Research proficiency was found to have improved without negative trade-offs to our students' engineering skills; in fact, it would seem that our students were able to apply knowledge from the context of research to the benefit of engineering-related learning activities. The paper ends by summarizing the conclusions. We find that research training can be helpful in teaching students the diametrically opposing aspects of thinking required by current engineering processes. We also conclude that teachers should grasp opportunities for students to learn about different perspectives of knowledge production as engineering education evolves towards more cross-disciplinary cooperation.

1.1 The research-teaching nexus

The connection between research and education, the *research-teaching nexus*, is much debated. Researchers take differing standpoints, including that this link supports synergies [14], has no substantial impact [15], or can be harmful [16]. Supporting each standpoint is complicated due to the many opportunities for variations. For instance, the conceptualization of research and teaching varies [17]; the strength of the relationship differs across institutions, disciplines and levels of education [15, 18]; and the entity/activity in focus can vary from teacher/teaching, to student/learning, to policy, to recruitment, and so on [19, 20]. Furthermore, curricula are also affected by occurrences at the societal level [21]—emphasis in engineering education on theory and scientific skills vs hands-on problem-solving and non-technical skills has varied across nations and throughout history. Nevertheless, the idea of a connection between research and teaching remains appealing to many in the academic profession [15].

Several reports have discussed the research-teaching nexus in regard to higher education contexts. In the US, the Boyer Commission [22] propose basing education at research universities on research and inquiry from the first year onwards. In Canada, Halliwell [23] strongly emphasize action towards creating a common vision on the research-teaching nexus among higher education stakeholders. In Australia, Cherastidtham, Sonnemann and Norton [24] down-play the importance of the research-teaching nexus for deciding between teaching practices in higher education. Tight [7], as part of a larger research project, summarize many of the national and international perspectives on the research-teaching nexus. Prince, Felder and Brent [25] identify that the most empirical support for a positive benefit of strengthening the research-teaching nexus comes from interventions where teaching has been shifted towards emulating the research process, rather than conveying research content. Together, these reports highlight how teaching practices, levels of education, institution and geographical location can all combine to complicate the study of the research-teaching nexus in higher education. When it comes to master's programs, even when limiting oneself to Europe and North America, the challenge is further evident in how students can be taken in drastically different directions [26–28]: the underlying intent of a program can range from preparing students for a career in academia to putting emphasis on skills required in professional positions in the industry.

The research-teaching nexus seems especially weak at engineering institutions [29]. Griffiths highlights the attitudes of both teachers and students to explain this phenomenon [30]. In regard to teachers, an explanation is likely the large proportion of academic staff recruited from industries in which orthodox science has little value in day-to-day operations [30]. Academics at engineering institutions are also aware that research in their fields is usually driven by government policy and industry, rather than by research institutions [30]. In regard to engineering students, an explanation is likely that these emphasise hands-on skills rather than methods to recognize and handle complexity [30]. The perspective is often that academia overemphasizes science, generating engineering students with too little experience in the practice of engineering and design [8]. Most studies on the research-teaching nexus are conducted in an undergraduate setting [10], where it is assumed that the case for a relationship is weaker [31]. However, there are exceptions such as the study by Aditomo et al. [32], which provides examples of different types of learning tasks used in disciplines akin to engineering at the undergraduate and graduate levels. These tasks are defined as inquiry-based, and several more or less mimic research activities. When characterizing which of these *"can be regarded as close to the kinds of research that academics engage in"*, one can argue that Aditomo et al. [32] use standards at odds with much of the research conducted in engineering. This suggests that the perceived weakness of the research-teaching nexus in engineering may be based on different conceptualizations of research.

Arguably this indicates that the complex relationship between research and teaching makes it difficult to ignore the influence of the subject content when looking at changes to research training. Strong opinions of teachers and students in engineering, and implications for knowledge production, suggest research has special implications for various types of teaching and the self-regulation of learning itself. Therefore our aim calls for a theoretical base that can be used to discuss psychological concepts as they relate to a wide range of other factors that affect teaching and learning activities.

1.2 Conceptual framework

To carry out our study we require a conceptual framework that can be used to (a) describe our intervention, (b) analyse the results and (c) discuss the outcomes.

The search for a framework suitable for our purposes started with the intent behind our study as it relates to the *discussion* of the outcome. As mentioned, it will depend on a wide range of factors involving both the individual student and the institutional context. To this end we chose Entwistle's model of the teaching-learning process as a conceptual foundation for discussing our results [33]. In contrast to many other similarly broad frameworks, it has a strong construct validity and has been developed for the context of higher education with an eye towards ecological validity [34, 35].

Entwistle's model is based on the two dimensions of *deep* vs *surface approaches to learning*, and *strategic* vs *apathetic approaches to studying* [33]. A deep approach to learning is trying to understand the underlying ideas of the learning material, while a surface approach to learning is to focus on the learning material and what it explicitly conveys [36]. A strategic approach is to optimize the time spent in a deep vs surface approach to learning to get the highest possible grade for the least effort. A deep approach to learning can be undertaken in a *holist*, *serialist* or *versatile* way [33]. The holist style is broad and personally structured, while the serialist style is critical, cautious and step-by-step structured. Students with a holist approach thus tend to try to get to an understanding of the learning material as a whole, only looking at separate parts based on mood and interest. Students with a serialist style instead tend to try to break down the learning material into a series of logical steps, only arriving at generic conclusions later by combining what has been learnt in isolation. The versatile style is to alternate between the holist and serialist styles to avoid the negative effects of taking either to the extreme.

However, to *analyse* our results we required a taxonomy that describes student *learning activities* in more detail than Entwistle's model. We chose to use the taxonomy by Vermunt and Verloop [37], since it is student-centred and shares enough background with Entwistle's model to allow the discussion to be related to the analysis [38]. The Vermunt and Verloop [37] taxonomy differs between cognitive, metacognitive and affective learning activities: cognitive activities process subject matter, for instance by structuring or analysing it; metacognitive activities plan the learning process, for instance by orienting the student in regard to what to learn; and affective activities involve dealing with emotions that arise during learning, for instance by actively focusing on learning rather than alternative activities. A student who realises that he has not understood a text although he has read it several times (monitoring, a metacognitive activity), overcomes the frustration related to this (dealing with emotions, an affective activity) and proceeds to focus on distinguishing the main points of the text (selecting, a cognitive activity) has passed through all types of learning activities. All parts of the taxonomy are identified in Table 1, with those important to this study described in further detail in the Results section.

To *describe* our intervention we used the model by Griffiths [30] to conceptualize the links between research and education. It defines four ways to structure the research-teaching nexus: *research-led* which organizes education around state-of-the-art research content; *research-oriented* which emphasizes the teaching of research-related processes, skills and worldviews; *research-based* where learning takes place through inquiry-based activities not

Table 1. Taxonomy by Vermunt and Verloop [37]

Cognitive	**Metacognitive**	**Affective**
Relating/ Structuring	Orienting/Planning	Motivating/ Expecting
Analysing	Monitoring/ Testing/ Diagnosing	Concentrating/ Exerting Effort
Concretizing/ Applying	Adjusting	Attributing/ Judging Oneself
Memorizing/ Rehearsing	Evaluating/ Reflecting	Appraising
Critical Processing		Dealing with Emotions
Selecting		

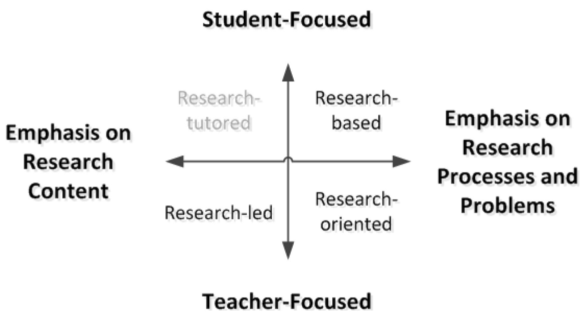

Fig. 1. Healey's [39] elaboration of the model by Griffiths [30].

necessarily focused on learning subject content; and *research-informed* in which the teaching and learning process itself is inspired by systematic inquiry. Using results from recent research studies as examples during lectures is thus a research-led approach, while involving students in research activities is an example of a research-based approach. Healey [39], as shown in Fig. 1, makes the point that these categories differentiate both teacher/student focus and research content/processes emphasis. This captures the essence of our intervention, which involved a shift across both of these scales.

Figure 2 summarizes the conceptual framework of the study. Using Griffiths [30] model we can describe a shift away from teacher-led and content-focused research training. We expected a student- and content-focused approach to allow students to become more independent and efficient when performing research activities, which should lead to improved outcomes in research-intensive learning activities. However, we feared that this would also lead to negative trade-offs with students adhering to the hypothetical-deductive model even when inappropriate during engineering design [40]. This should be observable using the taxonomy by Vermunt and Verloop [37] if students e.g., showed less consideration of design alternatives (see e.g., Relating/Structuring, Analysis and Selecting), emphasised a non-repetitive process (see e.g., Analysis, Appraising and Orienting/Planning) or ignored uncertainty (see e.g., Selecting and Orienting/Planning). This does not mean we believe that these problems are intrinsic to the hypothetical-deductive model, but rather that these trade-offs might occur when a *novice* to both research and engineering combines learning about both. This is the reason we need Entwistle's [33] model to discuss the implications of our results in the context of higher education.

2. Methodology

This section motivates and describes the research design of the study. It starts by establishing the background and studied intervention. Thereafter the methodology is motivated: first the overall choice of approach, and then each method in regard to validity and limitations.

2.1 Background and context of the intervention

By 2007 higher education in Sweden had adapted to the European Bologna process [41], which is based on three degree cycles [42], with a linear progression from bachelor to PhD using the master's as an intermediate step. For Swedish universities, preparatory change started earlier—with a stricter focus on research training already initiated in 2003. At our university, KTH Royal Institute of Technology in Stockholm, this meant the launch of a number of pilot programs. The existing 5-year professional engineering programs were divided in two: bachelor's (3 years) and master's (2 years). At the master's level, course-based programs were formed incorporating both professional and research-related learning goals.

The context of our study is a master's program, more specifically the Mechatronics Track of the Engineering Design master's program. During the first half of the second year a team-based capstone course integrates the knowledge gained throughout the students' engineering education, assessing whether they have the engineering skills required to develop products, processes and systems [43]. The second year then ends with a master's thesis course in the subject of Mechatronics, which assesses the students' research proficiency and *individual* mastery of engineering. It is thus not an option to, as some institutions, allow theses that focus almost

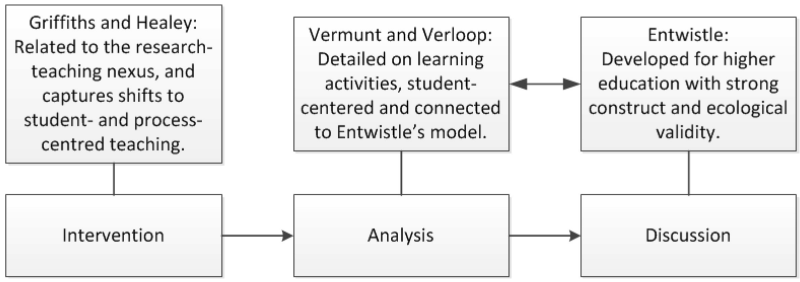

Fig. 2. Summary of conceptual framework.

exclusively on either research or engineering [26, 44]. Historically the engineering tasks of our theses have mostly come from an industrial context with students physically located at industrial premises. To allow a dual focus and to keep the engineering relevant to industry this practice has continued for our master theses. Recent examples of our theses' engineering tasks thus include the prototyping of a classification system for tracking objects in autonomous trucks, modelling the unwanted pressure oscillations produced by auto-ignition in engine cylinders and designing a control strategy for dampening out vibrations in an active cabin suspension system. The students identify research questions for the theses, ideally supported by finishing the engineering tasks and proven to be valuable by academic literature. As an example, the intention of the thesis prototyping a classification system was to investigate ways of using machine learning to improve object identification accuracy despite signal noise and environmental factors. As during our capstone course there is regularly tension between learning goals and the expectations of industry. However, as in capstone courses [45], these are usually possible to overcome by focusing on communication and defining the responsibilities of all involved. In theory our master's program thus ensures a high level of proficiency both in research and engineering. In practice, earlier external assessments of the program indicated only an acceptable level of research proficiency at graduation [46]. A closer look even revealed large differences between individual students in this regard. This motivated an effort to change the situation by intervening in our context.

2.2 Intervention

Prior to the intervention, a comparison group of students from our division was established, henceforth referred to as Y0 Students, i.e. *Year 0 Students*.

During the first year we replaced the lectures on ongoing research projects at the department, which encompassed 3 European Credit Transfer System (ECTS) credits, i.e. 2 weeks' worth of a semester. To date, these lectures had been *research-led*, i.e. they were traditional lectures and their emphasis was on making students understand research findings. The replacement was *research-based*. The students were divided into groups and presented with a set of questions concerning competing research methods, processes and worldviews. These questions were to be answered based on real examples of research, elicited from self-study and a series of three seminars. In the seminars senior researchers from the Department spent an hour explaining their research and another hour answering students' questions. Rather than passively receiving information in lectures, students had to look actively for knowledge. After submitting a report answering the questions, the students received guidance in the form of feedback on par with that given when reviewing journal publications. Rather unsurprisingly most students had to resubmit the report several times, while continuing to interact with teachers and researchers. Thereby an increased responsibility for regulating the learning was taken by the students. The students that received this type of research training will henceforth be referred to as Y1 Students.

During the second year of the study, we changed the *research-oriented* approach of the remaining lectures of our research training (equivalent to 4.5 ECTS credits) to a *research-based* one. During the previous years these traditional lectures had introduced a number of research methods, processes and worldviews. Students had then studied these concepts in more detail while putting them together to form a master's thesis plan. The new approach still introduced these concepts in a lecture, as a way of putting all students on the same level. However, we then relied on a bottom-up approach whereby the students received most support *after* their thesis plans had been formulated. A random choice of students had to present their plans in front of the entire class at two seminars, receiving detailed critique in the process. All students were expected to consider this feedback before handing in their final report. The students that received this type of research training will henceforth be referred to as Y2 Students.

Table 2 summarizes the treatment of the three cohorts of the study. As can be seen the treatment of the Y2 cohort was an extension of the treatment of the Y1 cohort, and involved a shift towards a more student- and content-focused approach.

2.3 Choice of overall methodology

We wanted to verify that the intervention improved our students' research proficiency. Furthermore, the focus of the study included the causal relationships connecting any improvements to the interven-

Table 2. Study cohorts and their treatment

Course Theme	Y0 Students (22 Students)	Y1 Students (28 Students)	Y2 Students (25 Students)
Research at the Department, 3 ECTS credits	Research-led	Research-based	Research-based
Research methods, processes and worldviews, 4.5 ECTS credits	Research-oriented	Research-oriented	Research-based

tion, especially as related to negative trade-off to our students' engineering skills. This first requires the nature of the improvements to be identified. On the one hand, the nature of improvements could be related solely to the students' grasp of the subject matter; on the other hand, it could be related to the students' way of self-regulating their learning activities. This means that the study had to include both confirmatory and exploratory elements [47]. With our Division being occupied with a multi-disciplinary research field, many of us share a pragmatic worldview [48]. It is therefore not uncommon for us to adapt or mix different types of research approaches, since proving an effect and understanding it better can often be best supported by different methods [49]. A way to build on different types of research approaches to include both confirmatory and exploratory elements is to use a *mixed methods design* employing a *sequential explanatory strategy* [50]: a phase employing quantitative methods precedes a qualitative phase. We decided on this approach since it allows for quantitative results to *direct* qualitative data gathering. Studying the self-regulation of learning solely with a quantitative approach would be difficult considering the many confounding variables related to any dependent variable; however, without first confirming an effect on specific cohorts, it would also be difficult to know which of our cohorts had changed enough to motivate a detailed study. The following three subsections describe the approach of the different phases, and the triangulation of their combination.

2.3.1 First part, confirming an effect

To confirm an improvement, and allow for a study of its nature, we measured a part of the curriculum with strong opportunities for both self-regulation and research. The choice fell on the master's thesis course, since it is driven by the students themselves and has research-related learning goals. This course is also separate from those that made up the intervention. We decided on the completion time as the dependent variable, as increased research proficiency should translate into more independent and efficient self-regulation of research-related activities and thus a shorter completion time. Self-regulated changes to completion time should also be readily measurable as there is no time limit imposed on finishing the course – each student decides when to submit their thesis. The characteristics of the data and cohorts motivated the use of a Kruskal-Wallis H test [51, 52]. For reasons of brevity, this motivation is given in the next section on validity and limitations.

The design was *quasi-experimental*, given that we intervened on groups that had not been formed through random selection [53].

2.3.2 Second part, Understanding the effect in depth

To explore a phenomena as complex as research proficiency, we followed Creswell's suggestion to use a qualitative analysis of qualitative data [49]. We considered our students' inexperience in research terminology the largest obstacle to analysis. Therefore, we chose to use inductive content analysis as outlined by Cohen et al. [54]. In line with this we each separately read through and coded all master theses, creating codes inductively. The textual definitions provided in the theses were helpful in avoiding misunderstandings: the use of research-related terms was unorthodox in several cases. The final sets of codes were discussed, merged and refined into categories during two work sessions. This ended in the creation of primary categories around learning activities defined by Vermunt and Verloop [37].

2.3.3 Triangulating the parts

To further corroborate findings, the quantitative and qualitative phases can be methodologically triangulated [55], i.e. positive/negative results from one method can be corroborated by positive/negative results from another. To allow for this corroboration, subgroups of theses from each cohort were identified by use of completion time and four qualitative variables indicative of an effect.

The four variables were the master theses' grade, research questions, methodological approach and discussion content. The choice of the latter three was based on the Tashakkori and Teddlie [56] framework for describing research studies.

To elicit subgroups the variables were (re)classified as dichotomous variables. The reasoning behind the assessment of the latter three variables was then coded directly into the theses to ease analysis.

For completion time, we divided the theses into two groups based on the average completion time.

For grades, we divided the theses based on whether they achieved an A grade according to the ECTS. With one exception, our examiners only handed out A and B grades. It should be noted that grades A to E all signal a pass, meaning that all theses reported in this paper were deemed to be acceptable overall.

For research questions we separated theses with high vs low quality research questions. High quality was defined as providing direct guidance to the direction of the investigation conducted during the thesis. This was in contrast to many research questions, which only indicated which area the study should be conducted in. To show the gist of this classification some examples are given in Table 3.

For methodological approach, we divided the theses according to whether they included a struc-

Table 3. Examples of research questions using quotes from theses

Low Quality	High Quality
"The purpose of this thesis is to investigate if the estimation of vehicle mass of an HDV can be improved if the road grade is retrieved from a map database instead of not using it."	"Sub questions that arise are: what are the advantages and disadvantages with an automated environment, in terms of effectiveness, safety and time? Does it add uncertainties into the testing process?"
"Develop a control strategy for two electrically actuated bypass valves that operates the exhaust gas into two separate TEGs with the condition that the exhaust gas do not overheat and damage the TEGs."	"How does the new media affect the stability and responsiveness when applying the multicopter techniques' under water?"
"What robust control strategy can be designed and implemented on an active damping test rig in order to reduce vibrations on a forwarder cabin?"	"Can the system given a reasonable guess of initial system settings optimize the process with regards to robustness, capacity and efficiency?"

Table 4. Examples of methodological approaches using quotes from theses

Low Quality	High Quality
"The project started with an extensive research on solutions to this problem and by delving into the current system used at [Firm]. After the initial research, the development process took the shape of an iterative methodology although no textbook procedure was applied."	"To be able to present such a result, data will be gathered by interviews and literature analysis."
"The first part of the thesis consisted of learning about EMG measuring, and the demands and limitations that could relate to the thesis . . . Once the information had been stripped down to its most basic fundamentals that related to the thesis, focus was changed to the technical aspect, meaning the specific components and their technical data that would be used in the project . . . For a project of this size and organization complexity consisting of only one person, a macro cycle version of the V-model was used since it would provide a systematic and logical approach to the different areas of interest during the project . . ."	"The idea was, through a case study, to explore the possibility to transfer the stabilizing and manoeuvring platform techniques' from airborne multi-copter vehicles (multi-copters, quadcopters etc.) to a new medium."
[No methodology discussed or used to structure the investigation of the research questions.]	"Once the model strategy has been chosen and the model has been built in MATLAB/Simulink, measurements from a [Firm] LNG truck will be used to verify the model through simulation by supplying the model with the same input as the real tank in the measurement. Furthermore the hold time of the tank model will be simulated and verified against indicative data provided by the tank manufacturer. Once the model is verified, the computational time and the processor load of the developed model will be analysed, together with an observer solution in the form of an extended Kalman filter, that will be tested on the model and evaluated, both with respect to performance and processor load."

tured empirical investigation beyond the ad hoc development of engineering artefacts. Examples primarily included case studies, but there were also questionnaires and interviews. To show the gist of this classification some examples are given in Table 4.

For discussion content, we divided the theses according to whether the discussion in them reflected a serious attempt at critical inquiry. This was defined as going beyond addressing the research questions by simply stating the capabilities of any system engineered as part of the thesis. While perhaps not a problem in the context of many other countries, this is a real risk in Sweden: as mentioned, our master theses are almost exclusively performed with students physically located at industrial premises, where hands-on engineering is emphasised. To show the gist of this classification some examples are given in Table 5.

2.3.4 Summary

To ease the understanding of the relationship between phases the important points from previous subsections are visualized in Fig. 3.

To ease the understanding of the relationship between data sets the important points from previous subsections are visualized in Fig. 4.

2.4 Validity and limitations

As Creswell and Miller did, for validity, we "most closely align ourselves with the use of systematic procedures, employing rigorous standards and clearly identified procedures" [57]. In the following subsections we discuss our approach to validity,

Table 5. Examples of discussion content using quotes from theses

Low Quality	High Quality
"The goal of this project was to research scheduling algorithms for multi-core embedded systems . . . several algorithms have been studied and compared. The linear clustering algorithm was chosen to be implemented. In the practical phase a toolchain for programming parallel applications was implemented. The target platform was the Epiphany E16 development board. Different software modules for that target had to be implemented . . . Several experiments were carried out in order to help evaluate the performance of the system. Parallel computing should only be used when there is enough computation to be parallelized. If there is little parallelization to be done, the mailbox system is not worthy to use. However, the execution can still be sped up by using algorithms based on task duplication. A mailbox system is worthy to use in applications with a lot of parallelization because the communication overhead can then be neglected."	"Among the three measuring procedure concepts of the DOC, the HC-slip test seems to have the highest potential to measure the oxidation performance of the DOC. In comparison to the NOx transient test, it has the ability to measure the performance of the DOC alone. Also, it is not dependent on the condition of neither the SCR nor the NOx-sensors. In comparison to the comparative test, it show tendency to be able to measure the oxidation performance and has fewer model dependencies. It also has a higher potential of measuring the light-off temperature. Since Concept 1 show tendency to be able to measure the oxidation performance of the DOC, the used exhaust mass flow in the tests seems to be sufficient to stress the DOC to obtain a measurement of the performance. Since the resolution of the results is still undetermined, it is not possible to decide whether if it could be lowered or must to be increased further. The HC-slip concept included some drawbacks, such as long duration time and troublesome temperature regulation. These drawbacks have to be investigated further, to find potential improvements of increasing the efficiency of this test."
"In the implementation in this thesis of the troubleshooting application, the main areas for improvements are the correctness of the Bayesian model, and a more complex troubleshooting algorithm. However, since the purpose of this thesis was to demonstrate how an integrated troubleshooting system that uses Bayesian network models for preparation of an action plan, it's natural that these were not as optimal as they could've been. The troubleshooting algorithm, as mentioned earlier, only looked one step ahead in time and never considered the possibility to conduct a test later in time. This limited the efficiency of the algorithm heavily, but the efficiency was sufficient enough for the implementation in this thesis. Since the troubleshooting algorithm depended heavily on the outcomes of the Bayesian network model and its probability distribution, it's concluded that for a successful troubleshooting (in the sense of minimizing repair cost and minimize downtime of the vehicle), both the model and algorithm need to be as optimal as possible. Hence, both are an area of focus for future work."	"The system in an application will have multiple benefits compared to a traditional static system. One of the main being the reliability of operation to be expected after the initialisation phase has passed. This reliability of operation is due to the level sensors, emergency mechanism and evolutionary learning from earlier cycles. For the traditional conveyor a source of machine downtime is failure of the filter caused by overfilling with material . . . Another large benefit of the optimisation is that due to that the system can without risk be operated closer to maximum performance, the system can therefore be used more efficiently or in new applications . . . A mayor question regarding this thesis is how to relate the measured performance improvements to what could be expected to be achieved by an operator? This is of course a question without a definitive answer since it will depend on the operators' level of skill and time assigned for the task. A skilled operator that has long experience will of course use that experience and achieve good performance of the system within a relatively short time-span with high probability. If the operator instead is a novice the time required will probably increase significantly. The novice operator will also face the problem of identifying behaviour that may lead to problems in the long run such as robustness issues due to too heavy plugs forming that he or she has not encountered before . . . Another large issue that needs to be addressed in the process in creating a product of this technology is how it should be implemented. One vision is to create an optimisation system that is add on to the conveying system and runs the optimisation until the operator is content with the results and then aborts and removes the extra equipment. That equipment can therefor consist of high quality components and be expensive as it will be able to service a large number of machines. Another approach is to have complete system distributed on all locations and create a database of solutions that have been proven that can be distributed to benefit all. The step of taking this technology from the laboratory to the factory will raise some ethical aspects on if such technology should be released on all markets and applications . . ."

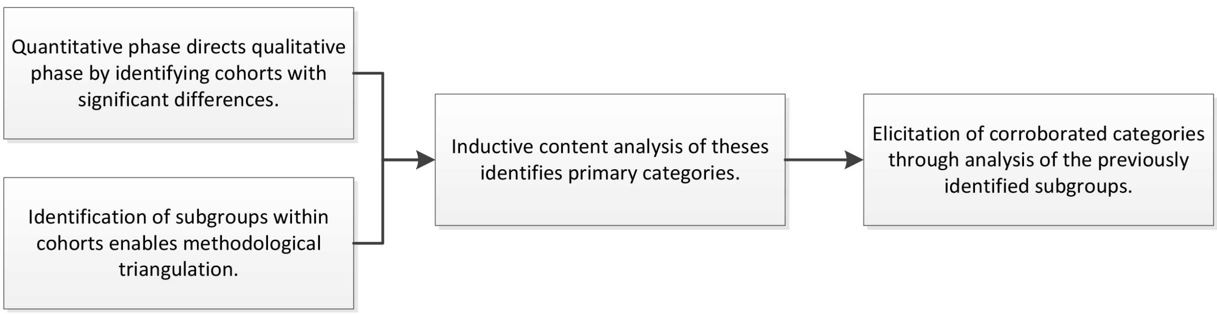

Fig. 3. The relationship between phases.

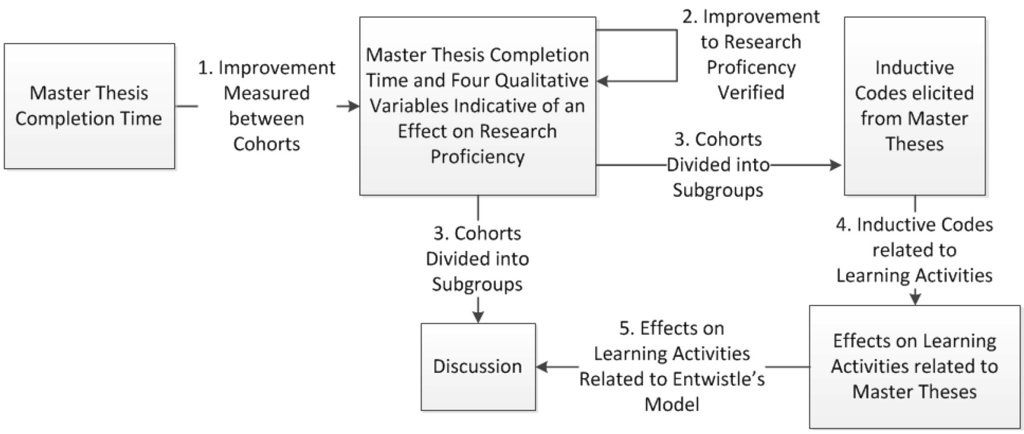

Fig. 4. The relationship between data sets.

important validity concerns and associated limitations.

2.4.1 *The complete study*

Due to factors out of our control it was not possible to use a true experimental or stronger quasi-experimental design [58]. These factors included gaps in previous data sets, that the curriculum could not differ within year groups, and that practically comparable control groups were not available. Therefore, the methodological triangulation was an important measure to ensure validity, given the difficulties in ruling out alternative explanations in quasi-experimental designs [59]. However, several alternative explanations still merit a discussion in the following paragraphs.

Prior to this discussion a reminder on statistical significance and power is valuable [60]. A required sample size is calculated a priori using the statistical significance, statistical power and effect size that make sense for each test at hand. We have no control over the size of our cohorts, and we have therefore identified underpowered tests in our study. We proceeded anyway, arguing that the triangulation allows for this, but it *still* has two key implications: firstly, when identifying significant results in underpowered tests, we have to discuss the associated effect size; secondly, when identifying non-significant results in underpowered tests, these cannot be used to accept the null hypothesis, due to the large probability of a Type 2 error.

The first alternative explanation considered was that the groups differed in some other aspect than the treatment they received [59]. At a cursory glance, the recruitment of women (5%, 11% and 4%, respectively) and students with a bachelor's degree from another university than KTH (18%, 18% and 16%, respectively) are similar across the cohorts. All students were full-time students. For a more detailed inspection of the differences between cohorts, we turned to their grades and ages. We essentially considered these as a *rough* indicator for large differences in maturity and capability.

For the grades we conducted a one-way ANOVA [61]. Grade averages were based on the time spent in the master's program and official calculations used when deciding scholarships/grants. Test data is summarized in Table 6. Student grades increased from Y0 Students ($n = 22$, mean = 3.8, $SD = 0.33$), to Y1 Students ($n = 28$, mean = 4.0, $SD = 0.33$), to Y2 Students ($n = 25$, mean = 4.1, $SD = 0.33$), but the differences between the student groups were not statistically significant. We argue that we can thus be acceptably sure that the groups do not differ significantly in regard to grades.

Table 6. Grade test data summary

Sample Size Calculation		**Test Results**	
Minimum detectable difference	0.5 grade step (considered minor)	Outliers	No (assessed through boxplot)
Standard deviation	0.5 grade step (expected based on previous year groups)	Data normally distributed	Yes (Shapiro-Wilk's test ($p > 0.05$))
Power	0.8 (standard)	Homogeneity of variances	Yes (Levene's test for equality of variances ($p = 0.945$))
Calculated sample size (one-way ANOVA)	21 students/cohort	Test statistics	$F(2,72) = 2.315$, $p = 0.106$

The age test data is summarized in Table 7. Outliers in, and the distribution of, the data indicated that the Kruskal-Wallis H test [51, 52], a nonparametric method, would be appropriate. It is difficult to establish a required sample size for this method [62]. However, an estimate based on rule-of-thumb and the one-way ANOVA sample size calculation show that we are within bounds [62]. The mean rank of ages was not statistically significantly different between groups. We argue that we can thus be acceptably sure that the groups do not differ significantly in regard to age.

We can also assert that there were no substantial changes to the acceptance criteria for the different student groups. Furthermore, the examiners at our Division didn't notice any large differences in regard to student capability between the cohorts, and the findings presented in this paper regarding the Y0 Students fit well with our and the examiners' impression of the state of earlier year groups. Therefore we argue that we have covered the most plausible indicators for large differences.

The second alternative explanation considered was mortality, i.e. selective drop-out of participants [63]. A retrospective check shows that two Y0 Students never finished their master's thesis, whereas all Y1 and Y2 Students managed to complete theirs. We therefore argue that mortality is not a substantial biasing factor in this study.

The third and fourth alternative explanations considered were those of history and maturation, e.g., the influence of significant events other than the intervention. We note that there were no substantial changes to the curricula for the different cohorts outside the intervention. Furthermore, the master theses were conducted in similar contexts. However, two possible concerns along these lines merit closer examination.

Firstly, using completion time as a measure of self-regulation relies on all students and teachers in the study perceiving the same ideal completion time. However, the start of a few of our master theses was delayed by a whole semester. There is no natural deadline for these theses, while the normal cases are generally perceived by students as ideally ending before the summer vacations. Even if the delayed theses were considered in the quantitative phase, the use of the aforementioned categories could not be relied on during qualitative analysis. To avoid confusing the analysis, eight such theses, roughly evenly distributed, were therefore removed from the data sets. To err on the side of caution separate tests have been carried out to ensure that, had the eight theses been included, they would not have changed the statistical significance of any results.

Secondly, the behaviour of members of our faculty is important, since regulation of learning is driven by both students and teachers. In regard to supervision substantial differences across the cohorts are unlikely: the supervisor group was stable, and the supervision of students administrative and focused on technical expertise. Structural aspects of the thesis course are rather addressed by texts available via the Department's website. Furthermore, there is a substantial resistance to emphasizing research across the supervisor group, due to reasons outlined by Griffiths [30]. However, for full disclosure, we note that one teacher involved in changing the curriculum supervised one thesis from the Y0 Student cohort and one from the Y2 Student cohort.

The question of a uniform assessment is of greater concern, since examiners at our Division might not interpret the assessment guidelines in the same way. One examiner was also involved in changing the curriculum, and might therefore evaluate theses from later cohorts differently. Therefore a Kruskal-Wallis H test was used to identify differences between examiners in regard to completion time. One examiner had only handled one thesis, and since this was not an outlier we decided to exclude it from the analysis. This resulted in six groups (n = 12, 14, 20, 13, 7 and 8). Test data is summarized in Table 8. Mean ranks increased across the groups (27.58, to 36.57, to 37.18, to 37.42, to 44.36, to 48.94), but the differences were not statistically significant. With an underpowered test we cannot reject the null hypothesis based on these results. We therefore interviewed the examiners. Based on the interviews we could not identify any substantial differences in their understanding or application of the learning goals of the master thesis course.

Table 7. Age test data summary

Sample Size Calculation		**Test Results**	
Minimum detectable difference	3 years (length of Swedish education cycles)	Outliers	Yes (assessed through boxplot)
Standard deviation	2 years (expected based on previous year groups)	Data normally distributed	No (Shapiro-Wilk's test ($p < 0.05$))
Power	0.8 (standard)	Distributions of ages similar	No (assessed through boxplot)
Calculated sample size (one-way ANOVA)	10 students/cohort	Test statistics	$\chi^2(2) = 0.906$, $p = 0.636$

Table 8. Examiners test data summary

Sample Size Calculation		**Test Results**	
Minimum detectable difference	15 days (considered minor)	Outliers	Yes (assessed through boxplot)
Standard deviation	35 days (expected based on previous year groups)	Data normally distributed	No (Shapiro-Wilk's test ($p < 0.05$))
Power	0.8 (standard)	Distributions of completion times similar	No (assessed through boxplot)
Calculated sample size (one-way ANOVA)	106 students/cohort	Test statistics	$\chi^2(5) = 5.570$, $p = 0.350$

2.4.2 The quantitative part

Quantitative research considers data gathering a separate activity from inferences and therefore raises special validity concerns [64].

A quantitative concern was the diligence needed over a long period to avoid errors entering the data set. All quantitative data was therefore checked against external use. As an example, the completion time was gathered internally and checked against announcements for end seminars.

Another concern was the way some theses may appear to take longer to complete because they span several semesters, with varying vacation time in between. To avoid this effect, official vacations and weekends were deducted from relevant completion time data points. This is acceptable, since our students were all full-time students and it penalizes our statistical tests for significant differences.

2.4.3 The qualitative part

Using the framework by Creswell and Miller we can identify three procedures for establishing validity in qualitative research that are in line with our paradigm worldviews. These are triangulation, member checking and an audit trail [57]. The use of triangulation is, as previously explained, a cornerstone in our study. As alluded to in previous subsections we have also made use of member checking: we interviewed the examiners at our Division to establish whether our understanding of the master's program, results and conclusions were credible and trustworthy [64]. We believe examiners are in a position to correctly evaluate self-regulation of learning, since they are the other half of said regulation. We also had our study audited by a professor external to our Division. He was provided with the data, results and analysis of the study. Feedback was provided in written form.

Feedback from the member check and audit has been incorporated into the study and this paper.

2.4.4 Limitations

We believe cognitive and metacognitive learning activities were the most important considering our intervention, and that the research design was suitable for studying them. Furthermore, none of our students seemed particularly weak in affective learning activities, and our member check did not reveal any specific concerns in that direction. Pressure to complete early or difficulties in the students' private lives should thus not have biased the study. However, it should be noted that the research design does not allow us to say whether our results translate to cohorts with an overall different capability in this regard. As an example, a cohort of very motivated students might look for more information earlier when faced with research-related learning goals, and vice versa.

3. Results

This section describes the results from the two phases of the study in preparation for the discussion. Associated data is found in Appendices A and B.

3.1 Quantitative results

Outliers in, and the distribution of, data indicated the Kruskal-Wallis H test as appropriate. The test held no assumptions on the similarity of the shapes of the involved distributions, and the comparison had already been established as underpowered. Comparing the cohorts reveals that the distributions of student completion time were statistically significantly different between groups. Test data is summarized in Table 9. Subsequently, pairwise comparisons were performed using Dunn's procedure with a Bonferroni correction for multiple comparisons. Adjusted p-values are presented. This post hoc analysis revealed statistically significant differences between Y0 ($n = 22$, mean rank = 46.30) and Y2 ($n = 25$, mean rank = 28.48) ($p = 0.015$), but not in any group combination involving Y1 ($n = 28$, mean rank = 39.98). Estimating an effect size can be done by using the Hodges-Lehmann estimator (HLΔ) on the cohorts in question [65]. HLΔ is originally only intended to be used for distributions with similar shapes. However, it has been shown that HLΔ can be used in the case of symmetric distributions [66]. Inspection of a boxplot and comparing medians to means indicate that apart from a few outliers the completion time is

Table 9. Cohort test data summary

Sample Size Calculation	Test Results	
Underpowered, see Table 8.	Outliers	Yes (assessed through boxplot)
	Data normally distributed	No (Shapiro-Wilk's test ($p < 0.05$))
	Distributions of completion times similar	No (assessed through boxplot)
	Test statistics	$\chi^2(2) = 8.207$, $p = 0.017$

fairly symmetrical. HLΔ is estimated to 20.9 (95%: 6.4, 45.9) for the completion times of Y0 and Y2. We thus conclude that we can be acceptably sure that our intervention has had a significant effect on master's thesis completion time.

3.2 Triangulation

This subsection provides the distributions of theses based on the dichotomous variables used for triangulation. This gives eight subgroups in each table laid out according to completion time (from low to high on the y-axis), grade (from low to high on the x-axis), and the quality of research questions, methodological approaches and discussion content (low quality to the left and high quality to the right in each cell). To facilitate interpretation the optimal subgroup (low completion time, high grade and high quality) is highlighted in grey. The frequencies of all subgroups add up to 100% of the theses for Y0 and Y2 Students respectively, as directed by the quantitative result.

Results indicate that the improvement to completion time is strongly tied to improvements of aspects of our students' research proficiency: as completion time improves from Y0 to Y2, the groups with improved research aspects grow strongly. This growth is especially noticeable for the optimal groups. As an example, as seen in Table 10 only 18% of the theses by Y0 Students both finished prior to the average completion time and achieved an A grade. Of these theses none (0%) had a research question of high quality. As seen in Table 11 56% of the theses by Y2 Students both finished prior to the average completion time and achieved an A grade. When dividing these theses further one can see that 32% of all theses by Y2 Students belonged to the optimal group—they were optimal in regard to completion time, grade *and* research question quality.

The aim of the study was to understand any causal relationships between the intervention and improvements, and to identify any associated negative trade-off to our students' engineering skills. It is then beneficial to compare each type of subgroup in regard to the qualitative results. The causal relation-

Table 10. Y0 Completion time, grade and research questions quality

Completion Time	18% / 5%	0% / 0%
	50% / 9%	18% / 0%
	Grade	

Table 11. Y2 Completion time, grade and research questions quality

Completion Time	8% / 0%	8% / 4%
	8% / 16%	24% / 32%
	Grade	

Table 12. Y0 Completion time, grade and structure of empirical investigation

Completion Time	18% / 5%	0% / 0%
	45% / 14%	9% / 9%
	Grade	

Table 13. Y2 Completion time, grade and structure of empirical investigation

Completion Time	4% / 4%	12% / 0%
	0% / 24%	12% / 44%
	Grade	

Table 14. Y0 Completion time, grade and discussion reflecting critical inquiry

Completion Time	18% / 5%	0% / 0%
	50% / 9%	18% / 0%
	Grade	

Table 15. Y2 Completion time, grade and discussion reflecting critical inquiry

Completion Time	8% / 0%	12% / 0%
	4% / 20%	28% / 28%
	Grade	

ships could for instance be straightforward, i.e. that an improved research proficiency meant students could more easily fulfil the learning goals of the master thesis course. Any negative trade-offs due to the intervention should then be most obvious in the optimal groups. Trade-offs could also be contingent on the abilities of the student, in which case the middle subgroups should give indications of the nature of these dependencies. Even the worst subgroups (quantitatively speaking) are interesting, since these students seem to be the least affected by the intervention. This can for instance help in identifying differences between Y0 and Y2 Students that are unlikely to be related to our intervention.

3.3 Qualitative results

As previously noted, primary categories were formed around some of the learning activities defined by Vermunt and Verloop [37]. Below we list the four of these which differ substantially between Y0 and Y2 Students, as directed by the quantitative result. Apart from this, no substantial differences were found when comparing different combinations of subgroups. Furthermore, these primary categories do not indicate any negative trade-offs to our students' engineering skills. Indeed, almost all theses indicated students were strong in concretizing/applying learning activities [37], and even if the research aspects of the theses by Y2 Students had improved substantially the theses remained strongly focused on engineering. Therefore, while the learning activities described below were framed as applied research, they can more accurately be described as engineering influenced by aspects of research. The difference between Y0 and Y2 Students thus appear to be that increased research proficiency made Y2 Students able to handle engineering tasks in ways Y0 Students could not. Unfortunately this means that our results mostly limit us to discussing Y2 Students, as they do not provide a way of discussing Y0 Students in isolation. However, in the Discussion section this will allow for a focused explanation of the causal relationship between effect and intervention, as well as point to a troubling limitation of our intervention that will require future research.

3.3.1 Adjusting

Adjusting involves changing learning plans or goals on the basis of monitoring one's observations [37]. A primary category for Adjusting was seen when analysing the Y2 Students in regard to the quality of research questions (Table 11). 6 out of 12 students in the groups with low quality research questions had in fact started out with high quality research questions.

This was not only connected to students with a higher than average completion time. 3 out of 6 seem to rather have used it as a strategy to de-emphasize critical inquiry. In other words, by removing the direct guidance on the direction of the investigation, the discussion in the thesis could be kept generic. As indicated in Appendix B, Table 17, this for instance meant removing parts of research questions that directed the investigation towards identifying optimal solutions. As there is no course requirement to actually succeed in engineering such an optimal solution, the only real difference was that students could thus limit the investigation to an ad hoc engineered prototype—avoiding discussing the implications of other engineering choices. Instead the mechanical aspects of applying scientific methods seem to have been stressed, allowing students to refer to these to motivate a more narrow investigation. As an example, 2 of these theses utilized unstructured interviews to support their case, which was otherwise quite uncommon.

3.3.2 Analysing

Analysing involves breaking down a problem into steps highlighting important aspects [37]. A primary category for Analysing was seen in 4 out of 7 in the Y2 optimal group (7 out of 12 also counting theses sub-optimal in regard to grade) in regard to a discussion reflecting critical inquiry (Table 15).

The difference between Y0 and Y2 Students in regard to Analysing was connected to students breaking down the field context when deploying an engineered system into parts discussable in separation. As indicated in Appendix B, Table 17, this for instance meant discussing what adding or removing different parts of the engineered system implied, and discussing each part of the engineering process in relation to the end result. As an example, one thesis discussed the engineered system from the perspective of each type of sensor that could be attached to it. Many students rather simply referred to the capabilities of their complete system, where engineering had only been limited by the components available at the time. Another discussed engineered artefacts on a scale going from simulations to prototype, highlighting what each form indicated in regard to the use of a real system. This differed from many theses that went through the steps of an engineering process, but never challenged the initial assumptions regarding the system to be engineered formed at the start of the process.

3.3.3 Processing critically

Processing Critically (PC) involves arriving at one's own conclusions based on facts and arguments [37]. A primary category for PC was seen in 4 out of 7 in the Y2 optimal group (7 out of 12 also counting theses sub-optimal in regard to grade) in regard to a discussion reflecting critical inquiry (Table 15).

The difference between Y0 and Y2 Students in regard to Processing Critically was connected to students raising validity concerns in regard to their study, or arriving at the limitations of it. As indicated in Appendix B, Table 17, this for instance meant that they challenged their own attempts to verify that their system worked as specified, and suggested tests that would validate that they had built the right system rather than simply built a system according to a specification. As an example, one thesis analysed the installation of a system that measured vehicles passing an intersection, rather than, as most, accepting the associated statistics and guidance from industrial supervisors directly. Another discussed the effect of loose clothing, rather than user experience, when measuring the effect of different prototypes on body awareness. This came about due to user tests with people from many different backgrounds, which highlighted difficulties with using the specified sensors that had not been identified when researchers had tested the prototypes themselves.

3.3.4 Relating/structuring

Relating/Structuring (R/S) involves connecting different parts of the learning experience, e.g., by imposing a structure on the main concepts of an article [37]. A primary category for R/S was seen in 4 out of 11 in the Y2 optimal group (8 out of 17 also counting theses sub-optimal in regard to grade) in regard to the structure of the empirical investigations (Table 13).

The difference between Y0 and Y2 Students in regard to Relating/Structuring was connected to students structuring their empirical investigations into inter-relatable stages, or realizing several engineering concepts and comparing them to each other. As indicated in Appendix B, Table 17, this for instance meant that students identified what could not be verified using simulations and proceeded to test this using prototypes, and built several prototypes to investigate the limitations of different design concepts. As an example, during the writing of one thesis two fall-detection systems were built and the different aspects of these realizations compared. Another realized simulation models for vehicle steering and braking and then related these to field tests.

4. Discussion

To organise our discussion we divide it into three parts, relating our results to theory and practice, as well as discussing the need for further research.

4.1 Theory

In regard to the learning goals of our master thesis course, a surface approach to learning is to focus on building engineering prototypes without reflecting on the overall purpose or strategy. This was the approach of most of the Y0 Students. However, Y2 Students showed strength in (a) systematic planning at the process level (see R/S), and (b) breaking down the learning experience into separate logically debatable steps (see Analysis and PC). This is evidence of a serialist style of a deep approach to learning. At the same time Y2 Students showed an increased ability to analyse a situation from different perspectives, while organizing parts into a meaningful whole. This evidence of a holist style was evident when Y2 Students brought together aspects of their field context and discussed validity. It seems Y2 Students were more versatile, able to alternate between both styles of deep approaches to learning. Furthermore, Y2 Students utilizing a strategic approach seem better at directing their efforts to engage in a deep approach to learning (see Adjusting).

Learning approaches in engineering education have been discussed with regard to the research-teaching nexus, mostly in terms of the tension between convergent and divergent learning approaches [40, 67]. For the purpose of the discussion in this paper, the convergent vs divergent distinction can be equated with the aforementioned serialist vs holist learning styles. Convergent learning approaches are thought to be promoted by traditional "engineering science" curricula, which emphasize engineering analysis skills. These curricula are thus thought to be detrimental to skills in engineering design, which would instead benefit from fostering the ability for divergent inquiry.

Our results initially seem to point to an outcome in line with stressing convergent thinking. Theses converged quicker and in more of a step-by-step analytical fashion. However, rather than being detrimental to divergent thinking, our results point to a more versatile and strategic learning approach. This can be best understood as an increased ability to combine analysis and design to successfully create a working system, i.e. *engineering synthesis*. While Y2 Students structured their entire learning experience in a more convergent way, they did not approach each part in a more single-minded search for *the* truth.

It is therefore an important observation that these improvements to learning activities were primarily evident in the support for engineering tasks, and not in pursuit of independent research. The underlying mechanism for the improvements was not a simple re-enactment of research methods learnt during research training. The mechanism rather appears to be a transfer of key insights of the production of knowledge from the context of research to the context of engineering. In *general*, transferability of skills and knowledge is an often highlighted benefit of inquiry-based approaches [4]. In regard to research, this can *specifically* be contrasted with traditional lectures and reading material, which are often based in one worldview. Accounts of how to apply methods therefore often leave out underlying assumptions. These assumptions can, on the contrary, be concrete in discussions where students are allowed to independently assess competing worldviews and question researchers.

The important mechanism to support our students' understanding of how to integrate engineering design and analysis would seem to be two-fold: to not only stress top-down structuring in research training, but also the ability to think freely and creatively about confounding factors. The result was not restricted to the isolated examples used to describe the differences between Y0 and Y2 Students in the previous section. Several students that structured their engineering as a series of steps used their discussions on validity to bound their investigations. As an example, a student that performed a sensitivity analysis on a vehicle model provided reasons for why the model could for instance be invalid for a car with a driver, but then stopped at noting that this was a limitation of the results. In other words, these students were able to see their engineering as a means to answer a question reasonably well within identifiable limitations. Students unable to adapt this perspective often extended their engineering needlessly into efforts of unreasonable size or limited value. This dual emphasis is most likely supported by a pragmatic worldview, which routinely weighs the weaknesses and strengths of research methods against each other. As this skill takes time to learn the students were probably mostly affected by the idea that both quantitative and qualitative methodologies can be acceptable as long as the situation merits it. Interviews were used as an example to put this message across to Y1 and Y2 Students. Both structured and semi-structured interviews were motivated in a fictitious study presented to the students, but based on different goals and perspectives of the involved researchers. Although still uncommon, interviews were the most frequently used method by Y1 and Y2 Students in combination with otherwise quantitative case studies.

The perspective that research training is harmful to aspects of engineering associated with divergent thinking might thus be too simplistic. If the research training introduces students to the motivations of a variety of quantitative and qualitative methodologies, it might actually help them to integrate aspects associated with divergent thinking with aspects dependent on diametrically opposed thinking. In addition to the aforementioned differences in how Y2 Students handled validity and accepted methodological combinations involving qualitative methods, there were a few weaker indicators of this ability. Firstly, Y2 Students seemed to have systematically queried more stakeholders for information on the context of the theses. Ultimately, Y2 Students seemed more willing to search for information that contradicted their initial plans, and make changes to the steps in their engineering process if they seemed unlikely to succeed. Secondly, all theses by Y2 Students that achieved an A grade solely based on their engineering achievements seem to have started with a high quality research question. This might indicate that these students started by thinking through the many aspects of their engineering problem more thoroughly than other students.

4.2 Practice

If our students' understanding of competing research methods, processes and worldviews are key to the observed outcomes, then arguably the most difficult challenge to successfully applying our intervention is that most researchers are proficient only in a narrow set of these. We extended the invitation to take part in the intervention to researchers from across several different research fields at our Department, which helped us to largely avoid this problem. However, we appreciate that this might not be possible at other departments. Therefore, the main implication of our results to the practice of engineering education is the need for more cooperation between engineering disciplines.

Traditional learning environments in engineering education include laboratories, cooperative education and research [2]. While a single perspective on knowledge production can permeate these learning environments at any one program, division or department, there are probably differences between them. Current engineering practices include cross-disciplinary projects with a requirement for interpersonal and creative skills [2]. In the future, engineering students are thus likely to see more interaction with research and development at firms other than those traditionally affiliated with their engineering discipline, and with the traditional learning environments of departments teaching other engineering disciplines, or even non-engineering institutions. As engineering education develops in this direction we urge teachers to take the opportunity to include learning goals that involve understanding the knowledge production of these other disciplines. As our results indicate, understanding the production of knowledge in other professions and affiliated sciences might not only improve interactions across disciplinary boundaries, but also an engineering student's own engineering processes.

4.3 Further research

Transferability of skills and knowledge has been mentioned as a benefit of our intervention being inquiry-based. However, the discussion has been focused on the shift from research-related subject content to research-related processes, rather than the teaching-centred to student-centred shift. This might seem like downplaying the latter shift, given the aforementioned close resemblance between inquiry-based learning and research activities. Could not the *primary* reason for the observed improvements be the additional requirements on our students to carry out inquiries?

We do not make this claim, since we found the inductive categories related to learning activities to be connected to the optimal groups in regard to research aspects, completion time and grade. Had the improvement mostly been related to our students' critical thinking skills, we would for several reasons have expected to see the same type of change to learning activities across the whole cohort. Firstly, breaking down the field context into parts discussable in separation does not require that more than technical issues are discussed. Secondly, a longer than average completion time gives students more opportunities to discuss validity, especially if the engineering outcomes are not optimal. Thirdly, while a lack of connection to field tests might be related to completion time, these tests can be expected in an engineering process regardless of the structure of any overlaying investigation. The inquiry-based approach thus seems to be more of a vehicle for achieving our results than the mechanism behind them.

With this in mind, our results point to the disturbing issue that even though we did not see any negative trade-offs, there appears to be a group of students that are left behind by our intervention. This suggests that further research needs to be performed to identify the limitations of our intervention in regard to which students are affected by it and how. The relationship between our results and the form of inductive learning employed should then be a good starting point. It would be interesting to see whether inquiry-based teaching that more strongly mimics research activities could lead to the same results. Case-based teaching utilizing examples from previous years could also be used to make learning less abstract and thus potentially more easily relatable to our students' experience of engineering. How much this is a motivational issue is also an open question—does the lesser extent of constraint in the teaching activities associated with our intervention specifically encourage those students which favour hands-on skills to approach these activities with a surface learning approach?

5. Conclusions

Our intervention affected our students' way of self-regulating certain learning activities. This effect seems to be linked to both our context and our use of inquiry-based research training. Our pragmatic context ensured the research training encompassed competing worldviews and methodologies. Our inquiry-based approach enabled students to transfer research knowledge to engineering practice. In this way our research training did not manifest itself simply as an increased ability to conduct research independently, but rather as an ability to self-regulate learning activities towards achieving engineering synthesis. This suggests research training can be helpful in teaching students the diametrically opposed aspects of thinking required by current engineering processes. It also implies that teachers should use the fact that engineering education is evolving towards more cross-disciplinary cooperation to ensure students learn about different perspectives on knowledge production.

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Appendix A, Quantitative data

Table 16 includes the quantitative data on which this paper is based.

Table 16. Quantitative data, completion time (days)

Student Number	Y0	Y1	Y2
1	398	106	103
2	100	195	149
3	147	108	106
4	154	108	101
5	119	108	101
6	149	108	195
7	100	101	101
8	114	101	106
9	114	108	112
10	100	113	102
11	100	95	105
12	101	95	100
13	147	109	93
14	147	118	102
15	92	102	102
16	280	102	93
17	111	179	93
18	136	159	92
19	126	132	92
20	175	96	95
21	159	170	95
22	342	92	130
23		92	130
24		292	202
25		100	97
26		212	
27		216	
28		269	

Appendix B, Qualitative data

Table 17 includes examples from qualitative data on which this paper is based.

Table 17. Examples of qualitative data

Associated Learning Activity	Examples of Inductive Categories	Text Examples (Coder notes in square brackets)
Adjusting	"Left out agreed learning goals"	"Identify the optimal . . . in regard to robustness, cost, length of service and impact on the environment." [Not found in thesis] "How can the performance of . . . be verified? [Against field behaviour]" [Not found in thesis]
Analysing	"Field is heterogeneous"	"Materials: [Long list of materials to be analysed in separation]" ". . . highlighting the importance with interaction between different disciplines, such as the [Different important disciplines]"
	"Critical concepts"	"In this section the effect of adding additional sensors [of different types] are discussed." "The faults that have been tested are the following: [List of separate fault modes to be considered]"
Processing Critically	"Unsuitable verification?"	"More preferable would be to have done the tests in a pool, inside a house. To prevent disturbances the tests were performed . . . Because of this it is possible to expect that the tests presented here is repeatable with the same results . . . when performing tests in a reactor tank." "During the tests it was noticed that the cable did not disturb the [system] as much as expected." "When tests were conducted between ... there were some issues that could affect the outcome of the tests. The main issue was the lack of time for prolonged testing."
	"Complex validation"	"To improve the validity of these conclusions global methods can be considered and more simulations should be done in different speeds and with different parameter values." "The final prototype was tested with a group of users that had no previous experience with [intent of system] and with different background."
Relating/Structuring	"Models compared to field tests"	". . . evaluating the accuracy of two different vehicle models, comprising the steering system, against real car measurements." ". . . the prototype was used to perform tests that was not possible to simulate with help of the developed model."
	"Field to field comparisons"	"Three prototypes will be created to examine the behaviour . . . The outcome of the tests with this prototype will contribute to decisions made when ... for a second and third prototype." "To test which . . . panel would work best . . . both panels were . . ."

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Boundary spanning at work placements: challenges to overcome, and ways to learn in preparation for early career engineering

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Boundary spanning at work placements: challenges to overcome, and ways to learn in preparation for early career engineering

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ABSTRACT

The transition from engineering student to early career engineer is often difficult as not all skills that constitute effective engineering practice are formally taught. Work placements are suggested as a solution by providing opportunities to learn skills that academia is unable to teach. However, academic requirements for skills such as research proficiency can be overlooked in a work placement environment, since they are often seen as of little value to engineers. Nevertheless, through interviews with master's students that have conducted their thesis projects at a firm, their experience of boundary spanning to align academic and industrial requirements has been shown to prepare them for an (early) career in engineering by providing opportunities to learn informal professional skills. As the effect is moderated by the *motivation* of the individual firm for offering work placements, teachers need to consider this motivation when planning and preparing a student for such a work placement.

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1. Introduction

Increasing the use of learning environments other than laboratories is a way of improving the breadth of engineering skills taught at Higher Education Institutions (HEI) without expanding formal curricula (Jamieson and Lohmann 2012). Swedish engineering education thus frequently employs cooperative education with industry (Törngren et al. 2019), a learning environment that provides students with hands-on experience of what it is like to be an early career engineer. A prominent example of this is the Swedish HEI policy to allow master's thesis projects to be conducted at firms. In fact, in Sweden this is the norm rather than the exception, even though the research component of master's programs is now emphasised in the same manner as in other European countries (Davies 2009). The assumption is that cooperation centred on master's thesis projects will allow engineering students to span the boundary between researchers and engineers (The Ministry of Education and Research 1993), learning the practice required at the Research & Development (R&D) firms where master's students are expected to spend their careers. Rather than only acquiring the latest knowledge on technology, students should learn to gather, assess, analyse, create and share this knowledge during engineering design (The Ministry of Education and Research 1993). Previous work suggests that engineering students thus acquire research proficiency when writing their master's theses, but with an engineering perspective (Asplund and Grimheden 2019).

However, traditional research often solves problems that are disparate from those of engineering design and without business requirement constraints. Researchers can thus be oblivious

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to the limitations that engineering practice imposes on R&D (Dym et al. 2005). Similarly, the attitude among engineering faculty and practicing engineers towards research proficiency can be dismissive (Griffiths 2004). It is thus a considerable effort to bridge the expectations of both academia and industry on a Swedish engineering master's thesis project. This is a cause for concern, especially as the effect on learning outcomes by placing engineering students in firms for a prolonged time is understudied (Hadgraft and Kolmos 2020). In the worst case the academic requirements on showing research proficiency would not only be left unfulfilled, but may even interfere with the other learning that should come from being placed in an industrial context.

To explore this problem we focus on the students' *boundary spanning* between academia and industry during practice-focused master's thesis projects conducted at engineering firms. Boundary spanning is a generic concept, used to describe people spanning organisational boundaries to relate organisations to external elements (Haas 2015). The associated challenge is that the boundary spanner has to relate to several contexts that might be fundamentally different, e.g. organisations that have different goals, emphasise different knowledge, and reward different outcomes. This is very much the case for master's students conducting master's thesis projects, who enter work placements at firms with the intention to return after fulfilling certain academic requirements. Most obviously, these academic requirements might be in conflict with the outcomes sought by the firms. As an example, the academic institution might stress the rigour of the conducted research, while the firm might want to see a working prototype. If the academic institution and firm involved in a master's thesis project do not know each other well, such differences might be aggravated as both sides take precautions to ensure outcomes in line with their wishes. As a master's thesis project is an independent endeavour, the abilities and motives of the individual student will play a part in mitigating or aggravating any challenges due to differences between academia and industry. Even failing to grasp certain subtle differences between research and engineering might have an adverse effect. A student's plans might for instance allocate too little time to understanding the causal relationships to be proven, leading to the engineering of prototypes unsuitable to answer the research questions. In fact, the situation is even more complex than the organisations and students involved in this boundary spanning suggest, as the definition of the primary outcome of this boundary spanning – what the students should learn – is open to dispute. At the very least students should proceed from research questions to conclusions according to academic standards. However, research at firms with a focus on engineering systems will face other limitations and requirements than those most frequently encountered in academia. As an example, finishing a prototype critical to experimentation might be less related to missing knowledge than being able to persuade management and other engineers to provide necessary resources and expertise. If students gain such insights, or even learn associated informal professional skills during their master's thesis projects, it will be valuable to their continued work as early career engineers. However, this opportunity is not necessarily well understood by either academia or industry.

The focus of this study – to understand the antecedents to enabling boundary spanning during a master's thesis project to facilitate the transition of engineering students into early career engineers – is thus a broad topic. However, by focusing either on the challenges to fulfilling academic requirements under engineering constraints, or the difficulty in maximising the opportunities to learn from an engineering practice that involves research, the issues discussed thus far can be divided into two categories. On the one hand, the relationship between this boundary spanning and the challenges of conducting a master's thesis project, and, on the other hand, the relationship between this boundary spanning and the learning of engineering practice.

The next section provides a theoretical framework for our exploratory study and points at key concepts that are important to investigate. This is followed by our methodology section, describing the case we have chosen to explore. The results and analysis sections describe the outcome of our interviews, which is then discussed and summarised into conclusions.

2. Theoretical framework

This section describes the theoretical framework of the paper, which is based on the discourses on the research–teaching nexus and boundary spanning. Firstly, this exposition of literature suggests that no single discourse contains the theory necessary to allow a complete analysis of our results. Secondly, it exposes a paucity of extant literature at the intersection of the discourses on boundary spanning, engineering practice and engineering education. However, even if strong hypotheses cannot be defined, a perspective on how relevant concepts might fit together can be tentatively put forward.

2.1. The research–teaching nexus

The idea of whether the relationship between research and teaching (the research–teaching nexus) is positive or negative has been debated for decades, even centuries (Hattie and Marsh 1996). While often equated to the discussion on whether active involvement in research affects teaching ability, the discourse includes both the inverse influence of teaching on research and the wider perspectives on, for instance, the role of universities (Tight 2016). More specifically, it includes studies on the combination of teaching and research by *involving students in research* (Prince, Felder, and Brent 2007) or *utilizing inductive teaching* (Prince and Felder 2006). Swedish engineering master's thesis projects are examples of one or both of these, as they combine the independent solving of a complex, real-world engineering problem with a scientific study. The applied base means that they are examples of the most common types of inquiry-based learning in engineering programs (Aditomo et al. 2013). However, they are closer to scholarly research than usually is the case, as the students are largely independent in regard to choosing research questions, gathering data and performing data analysis. The Swedish master's thesis project is thus an introduction to the independent handling of research as part of the type of engineering that engineers in R&D firms are expected to carry out.

This type of learning is student-centred, meaning that students are required take on a large responsibility for their own learning (Prince and Felder 2006). On the one hand this can be an advantage, as inquiry-based learning provides an opportunity for students to improve their critical thinking, problem-solving skills, planning and motivation (Warnock and Mohammadi-Aragh 2016). On the other hand, for those students that are not sufficiently strong to begin with, the loose teacher-regulation of learning can lead to destructive friction in cognitive, metacognitive and affective learning activities (Vermunt and Verloop 1999; Wulf 2019). Not all students respond well to inquiry-based learning, but may instead be overwhelmed by it.

In regard to cognitive learning activities we note that Asplund and Grimheden (2019) suggest that an especially useful skill during engineering master's thesis projects is the ability to think freely and creatively about confounding factors. Being able to discuss the flaws of a research task can allow students to better control the scope of an associated engineering task. If the research and engineering tasks are disjointed, this will be more difficult. In regard to metacognitive learning activities we note that while inquiry-based learning is often highlighted as well suited to developing metacognitive skills, this takes time and depends on placing students in unfamiliar territory (Downing et al. 2009). In other words, having to fuse research and engineering tasks during a master's thesis project might eventually strengthen metacognitive skills, but success in this regard is not necessarily facilitated by inquiry-based learning. In fact, a failure to fuse research and engineering would likely result in a larger scope and more coordination between tasks, which would further aggravate a lack of metacognitive skills. In regard to affective learning activities we note that these are linked across the research and engineering tasks of a master's thesis project. They both relate to a student's current mood and thus influence the whole learning process (Vermunt and Verloop 1999). The ability to handle anxiety related to the uncertainty of the research process can be a large part in enabling a student to make necessary decisions in research situations (Wessels, Gess, and Deicke 2019). Similarly, the motivation of students can be affected by the difficulties in handling too complex engineering tasks without adequate teacher support (Catz, Sabag, and Gero 2018; Gero, Catz, and Sabag 2018). In other words, the more disjointed the research and engineering tasks of a master's thesis projects are, the more potential there will be for an affective challenge to surface that influences the whole learning process negatively.

This suggests that students who are able to *align the requirements* of academia and industry on the associated engineering and research tasks will increase their chances of successfully finishing their master's thesis projects. It will allow them to control the scope of the associated research and engineering tasks, reduce coordination effort, and limit the chances of negative feelings influencing their work. To achieve such an alignment students are required to span the boundary between academia and industry during negotiations with both.

2.2. Boundary spanning

While inquiry-based learning engenders the competence required to handle typical problems and tasks in professional engineering practice (Jungmann 2019), going beyond the attainment of formal professional skills still relies on *informal interactions* with peers (Johnson and Ulseth 2016). Unfortunately, curricula do not necessarily include the skills required for such informal interactions or the socio-technical complexity in which they occur in engineering practice (Trevelyan 2019). Attempts to socialise students into their professional identities already during higher education are often confounded by a strong emphasis on 'academic communicative practices, audiences, and goals' (Dannels 2000). Early career engineers instead become full participants in their profession foremost by informally engaging with, and learning engineering practice from, their community of practice (Lave and Wenger 1991). These groups provide a social context – both internally and between firms – that allows for knowledge sharing and thus reproduce (engineering) practice (Brown and Duguid 2001; Leonard and Sensiper 1998; Lesser and Prusak 2000).

However, elements of contextual, practice-related learning that enable engineering students to glean knowledge from their communities of practice *have* increased in engineering curricula (Hadgraft and Kolmos 2020). Although it is still more common in undergraduate than in graduate programs (Jamieson and Lohmann 2012), this could allow engineering students to quicken their transition to professional engineers. Naturally, this also increases the influence on learning by engineering firms, which have their own needs that motivate their engagement in higher education. While academia exposes students to firms to enable learning from real-world problems and technology, firms engage to get access to cutting-edge technology and technological consultancy (Ankrah and Omar 2015; Ozman 2009). Short-term projects allow firms to leverage students' engineering skills, state-of-the-art knowledge and research proficiency to solve their current engineering problems (Hasanefendic, Heitor, and Horta 2016). As part of an academic context, engineering students will thus have to reach out to a complex industrial context constrained by real-life business considerations to enable a scientific study. Even when such *boundary spanning* only involves recombining old ideas in new ways (Hargadon 2002), the complexity of the context can involve a diverse set of services both at an organisational and an individual level: intermediary organisations might have to provide foresight, information processing, gatekeeping, validation and commercialisation (Howells 2006), while individuals must handle information exchange, market access and coordination (Haas 2015). Successful boundary spanning under such conditions often depends on the perception of technical competence, and enough time to cultivate both formal and informal contacts (Nochur and Allen 1992). Indeed, cultural differences regarding openness and time management can require substantial (time for) trust to be developed before academia-industry collaboration can lead to meaningful knowledge transfer (de Wit-de Vries et al. 2019). Firms that have not established this trust to a university are likely to prefer to limit the research activities in any collaboration (Buganza, Colombo, and Landoni 2014), and might choose to involve themselves in projects with students, rather than faculty, for this very reason (de Wit-de Vries et al. 2019).

Therefore, trust should influence the contribution by boundary spanning to the learning of engineering practice through practice-based master's thesis projects conducted at engineering firms. Even if the paucity of extant literature does not allow for strong hypotheses, one can draw on separate theories to construct three cases with different implications for the associated boundary spanning:

- Cases where the targeted problems are of immediate relevance to the firm's current business.

○ In the first type of case, trust does not exist. In this case, firms will want to emphasise problem-solving based on well-formed requirements using best practice engineering and technology. Effort will go towards limiting the uncertainty introduced by research activities. Firms will most likely want to treat the engineering and research activities of the master's thesis project as separately as possible. Although there will be a need for boundary spanning, it will be strictly controlled, much like in professional project-based engineering capstone courses. The discourse on engineering education then offers several important insights, suggesting that students will be exposed more to formal project management (Bastarrica, Perovich, and Samary 2017), written communication (Fries et al. 2017) and technical (Howe et al. 2018) skills, than skills in negotiation (Bastarrica, Perovich, and Samary 2017), verbal communication (Fries et al. 2017) and budgeting (Howe et al. 2018). Any contribution to the learning of engineering practice by boundary spanning activities is thus likely to be related to formal engineering skills.

○ In the second type of case, trust exists. In this case the state-of-the-art knowledge held by engineering students can have a powerful impact by enabling the design of novel solutions. Arguably, this can be *the* reason a firm is willing to bear the costs of hosting a master's thesis project. The discourse on boundary spanning then provides several relevant insights. Students will most likely have to interact with the firms' gatekeepers, i.e. boundary spanners that bring knowledge from external sources into the firm and ensure that it is both understood and used (Paul and Whittam 2010). They will be asked to repackage and communicate knowledge (Cillo 2005), an aspect of gatekeeping that has become increasingly important over time as information technology has made pure knowledge transfer less valuable (Whelan, Donnellan, and Golden 2009). This is a substantial part of engineering boundary spanning, and is usually more informal than the communication skills taught in engineering curricula (Jesiek et al. 2018). As the tasks are of immediate relevance to the firm's engineering activities, the boundary spanning is also likely to require coordination of (and with) engineers within the firm to co-create common ground and build more trust. The uncertainty brought on by the research is likely to force the students to go beyond formal specifications, making such coordination more informal and akin to the informal technical coordination of engineering practice (Jesiek et al. 2018). Boundary spanning activities might thus contribute to the learning of engineering practice not only through the learning of formal engineering skills, but also by bringing about the need for associated informal activities.

- In the last type of case, the targeted problems are *not* of immediate relevance to the firm's current business. This can for instance be because the task is artificial, has a deadline set far into the future, or is of minor or no economic importance. On the one hand, trust is then unlikely to be as important, which suggests that students should have an easier time accessing engineers at the firm than in the first type of case. On the other hand, as the problems are of less relevance, these engineers might have less time, interest or useful expertise than in the second type of case. Whether boundary spanning provides opportunities for learning formal or informal engineering practices is more open to chance.

3. Research design and methods

This section provides a case description, positions the research as an exploratory case study, and details the data collection, data analysis and validation of the study.

3.1. Case description

This study is based on the Mechatronics track of the Engineering Design master's program at KTH Royal Institute of Technology. The last six months of this track consist of a master's thesis course, which assesses the students' research proficiency and individual mastery of engineering. Higher education in Sweden adapted to the European Bologna process more than a decade ago (Lindberg-Sand 2012). This meant that existing 5-year professional engineering programs were divided in two: bachelor's (3 years) and master's (2 years). The master's thesis course then came to replace what had previously been an engineering project course, usually carried out as an internship. Therefore, it still remains the expectation by most of those involved that the master's thesis course should be organised at a company and as a project that contains both research and engineering tasks.

Historically the engineering tasks of Swedish master's thesis projects have thus mostly been provided by industry, with students physically located at industrial premises. Recent examples of such engineering tasks include real-time local wave forecasting for power maximisation of wave energy converters, the design of novel control strategies for pin-on-disc tribometers, and the optimisation of sensor placement for training a neural network to detect anomalies in jet printing.

As for the research tasks of master's thesis projects, Swedish firms typically do not provide these as part of their master's thesis project offering. The research tasks, even the identification of research questions, are instead left for the students to manage. Therefore, students usually identify research questions that benefit from the output of the engineering tasks. When Swedish engineering firms provide a master's thesis project, it would thus be more correct to say that they provide a topic to study. This topic can be a problem that is difficult to solve by contemporary engineering, or a novel solution or method. It is then up to the student to identify something related to this topic that would be valuable to study according to the academic state-of-the-art.

Sixty-four students conducted their master's thesis projects during the studied semester. Of these, eight projects were provided by professors at the Mechatronics division, six were provided by professors at other divisions at KTH, and two were defined by students. The remaining 48 projects originated from different firms located across Scandinavia. We note that the high number of projects provided by academia during the studied semester was unusual, but that they did not affect the projects provided by industry.

The master's thesis course process is light-weight, as students are supposed to show independence throughout the course. However, they are allocated an academic supervisor, who – in the case of projects provided by industry or other academic divisions – primarily supports by answering administrative questions. When a project nears its completion, the student will hand in a master's thesis to their supervisor that describes everything that can be expected from a scientific study – from research questions to conclusions. If the master's thesis contains all the expected parts, then the supervisor hands it over to one of the professors at the division. This professor then assesses the master's thesis according to learning goals ultimately established by the Swedish Ministry of Education and Research (The Ministry of Education and Research 1993). This assessment is based both on a reading of the thesis and a presentation of it (at which another master's student serves as an opponent).

3.2. An exploratory case study

Three months prior to a new iteration of the master's thesis course the two authors started *thematising* and *designing* an interview study. The resulting interview script focused on how the students had planned for their thesis projects, how well prepared they felt, and which challenges they had encountered.

During the first three months of the master's thesis course a first round of *interviews were* then *conducted*, in which the authors interviewed all 64 students. Naturally, many of the concepts that make up the theoretical framework informed our thinking, but the interview script centred on the students themselves. Most importantly, we did not lead the students along by explicitly asking about the motives of, or relationships between, other actors. These interviews took half an hour to complete on average, but in some instances took a full hour. There were of course differences between the students, but overall their largest problem was with the boundary spanning between industry and academia. The different expectations by these two stakeholders often required considerable effort to handle. However, although perhaps largely lost on the students, the boundary spanning also came across as one of the largest learning opportunities in regard to understanding engineering practice. Although the first round of interviews was not immediately transcribed, we met once a week during the subsequent two months to discuss our impressions. This allowed further refinements to the theoretical framework described in Section 2. The available literature was still not enough to define hypotheses, but a more focused, second interview script could be designed. This interview script focused on challenges to industry-academia boundary spanning, and the relationship between the student and the provider of the master's thesis project.

Fifty of the students accepted to be interviewed a second time. Using the updated interview script, these students were interviewed during the subsequent six months after their theses had been accepted by one of the course examiners. Thirty-seven of these 50 students were placed at firms during their master's thesis project. These interviews took 20 min to complete on average, but in some instances took a full hour. Most of the interviews were conducted face-to-face, but when circumstances did not allow for it they were conducted over the phone.

All interviews from both rounds were recorded and *transcribed*. Twenty-four of the interviews from the first round were transcribed by the authors, while 40 were transcribed by a professional transcription service for the sake of convenience. Similarly, 24 of the interviews from the second round were transcribed by us, while 26 were transcribed by a professional transcription service. This transcription ran in parallel to the interviews, starting two months after the first interview and ending two months after the last interview.

The *analysis* and *verification* started one month after the last interview and took seven months to conclude. The interviews from the first found were analysed to ensure that our impressions were indeed well founded. The interviews from the second round were analysed to arrive at the results presented in Section 4. We met bi-weekly to discuss, merge and refer codes back to the transcripts and recordings. As the codes solidified, these bi-weekly meeting eventually included discussions regarding the results.

The *writing up* of the study started slowly during the analysis stage. However, most of the writing was performed during the two months after the analysis had concluded.

This study, performed as an explorative case study informed by interviews, thus took about 24 months from start to finish.

3.3. Data gathering

The interviews were designed as semi-structured interviews according to the procedure defined by Brinkmann and Kvale (2015).

We wanted to capture the students' experiences from boundary spanning across their entire master's thesis projects. Furthermore, the largest threat to internal validity was thought to be students self-censoring their critique due to concerns about their grading. Therefore, the students were not asked for a second interview until they had finished their thesis projects. This meant that most of the students were interviewed after they had already been hired and transitioned into early career engineers, providing them with further insights into the strengths and weaknesses of their engineering education.

Both interview scripts were designed to explicitly include several follow-up questions, which allowed interviewers to 'push forward' (Brinkmann and Kvale 2015). This also ensured that we were reminded to clarify the meaning of ambiguous statements.

To promote active listening and avoid researcher bias, both authors were present for 11 of the early interviews. During these interviews, we took turns either ensuring that the interview script was followed or focusing on the interviewee's responses. The other interviews were conducted by the author who had the earliest opportunity to conduct the interview.

To ensure the reliability of the data the professional transcribers were instructed to leave parts that were difficult to transcribe to the authors. Although interviews were performed both in Swedish and in English, to minimise mistakes only those performed in Swedish were referred to the transcription service. These two precautions ensured that the data analysis could identify ambiguities and refer back to the recordings in order to handle them. Similarly, all quotes presented in Section 4 were verified against the recordings and, when necessary, translated by us.

As the aim was solely to capture the meaning of the interviewees' comments, we had to decide on a reasonable level of detail in the transcripts to avoid confounding the subsequent analysis (Brinkmann and Kvale 2015). Therefore, transcripts only included details such as pauses, repetitions and emotional expressions when it was deemed to have a bearing on the interpretation of an interviewee's statements.

3.4. Data analysis

All interviews were initially coded with descriptive codes (Saldaña 2009a). The code book eventually included 61 codes. The codes' consistency in regard to meaning and application was ensured by discussions between the authors. To avoid misinterpretations these codes were based on explicit comments by the students. When in doubt, we referred back to the audio recordings to avoid misunderstanding interviewees due to detail that is difficult to convey when transcribing. This ensured that internal validity was not affected by unreliability of the coder or coding. The initial analysis was followed by a recoding of the descriptive codes to identify patterns (Saldaña 2009b), i.e. so-called 'Pattern Coding'. The resulting secondary coding aimed at interpreting the meaning of the interviews in light of the analytical framework (Brinkmann and Kvale 2015). The patterns, or groups of descriptive codes, thus iteratively identified, are reported in Section 4. The iterations ensured that the final interpretation was free of contradiction, and the traceability between codes ensured that it could be tested against its parts and available literature – an important part of analysing the meaning of interviews (Brinkmann and Kvale 2015).

3.5. Validation

As outlined in the previous subsections several actions were taken to ensure the internal validity, construct validity and reliability of the study: the initial interview ensured that the focus of the study was on a substantial factor in the studied context; the interview script and the use of several interviewers removed ambiguity; the large response rate ensured a complete coverage of student perspectives; to delay interviews to after the associated thesis projects were finished minimised the risk of false, biased or incomplete information; utilising several interviewers decreased the chance of interviewer bias; following up on uncertain transcriptions increased the reliability of data for analysis; analysing and coding as a group meant coder bias was minimised and coding reliable; and testing interpretations against each other and the available literature ensured consistency.

Despite these precautions, we were concerned that the 14 students we could not interview in the second round held unique perspectives on the concepts we explored. However, we could not get to these perspectives through triangulating with other sets of data or performing traditional member checks involving these students (Creswell and Miller 2000). Therefore, we instead asked the supervisors for these students whether they, based on their continuous interactions with the students, believed we had missed any relevant findings. None of the supervisors indicated that they thought this was the case.

Not all of our students had to engage with firms, and the diversity of HEI means that this is the default for the engineering students in some countries and master's programs (Davies 2009). Differences might also arise due to factors linked to geography, engineering disciplines, business domains, etc. However, there are also more subtle limitations in regard to the external validity of this study. These are addressed by a discussion in Subsection 5.3.

4. Results and analysis

This section starts by providing generic observations. This is followed by results and analysis related both to the relationship between boundary spanning and the challenges of writing a master's thesis, and to the relationship between boundary spanning and the learning of engineering practice. Throughout this section the firms that provided master's thesis projects are referred to as (industrial) thesis project providers.

4.1. Initial observations

The existence of trust between the industrial thesis project providers and the faculty at KTH's Mechatronics division were obvious to the students. They readily identified longstanding cooperation between the organisations, and found graduates from the Mechatronics track working at their industrial thesis project providers. (We note that these observations matched statements from the faculty on which firms they knew well.) Furthermore, in some cases the thesis project providers had come to trust the students themselves through previous internships. This meant that three out of four students that conducted their master's thesis project at a company did so in the context of a relationship based on trust. There was also evidence that this trust had been valuable to the firms. Students had for instance bypassed ingrained conceptions to identify novel technical solutions (Table 1).

Table 1. Examples of relationships based on trust.

Trusted academia	'I: So, did [the industrial thesis project provider] have any connections to the Mechatronics division that you know of? A1: Yes. I think [industrial supervisor] and [academic supervisor] has a connection. [Other industrial supervisors] did all that work with him a few times. Yes, definitely, yes, exactly. So, they have a good relationship with each other.' 'I: Do you know if [industrial thesis project provider] had any earlier contact with the Mechatronics division? A2: Yes, what is his name … [Manager at Mechatronics Division] has a very good relationship with [industrial supervisor] as they collaborated on setting up the Engineering Design master's program.'
Trusted through previous students	'I: Did anyone at [the industrial provider] know someone at the Mechatronics division? A3: Yes. My colleagues had been to certain courses in Mechatronics and they know a few of the faculty members.'
Trusted through previous internship	'A4: Actually, I also did my summer work there last year. That was a project, which … called … I forgot the name of that, but that is summer work plus master's thesis. So, last winter I did not apply for any master's thesis opportunities. They just gave me a list of the tasks this year, and I just found one of them … I: Did they just give you [emphasis on you] this list? A4: A number of others, but as I had the summer internship last year they gave me the priority to choose first.'
Reciprocated trust	'A5: Well, how should I put it? They were very much aware that what they suggested was not [academically] acceptable. Furthermore, I had been clear from my side that to get it accepted it would possibly have to be changed. Then it was not accepted [by KTH]. [Engineers at the firm] were very easy to discuss with, but at the same time there were requirements and wishes that I had to … Well, to get some value out of it … They had an inkling about that the new suggestion I was working on, the [topic of master thesis project], was something they should look at, but they thought other process parameters were more relevant for health data, which I then early in the project showed was not connected to the health of the machine … I: So, you showed them the right thing to focus on? A5: Yes, I did.'

Most students were also keenly aware that the thesis project providers had one, or a combination of several, reasons for offering master's thesis projects. Naturally, they often wanted a prototype of a new product or an improved version of an old one. There was the intent to 'test' the skills and personality of students before offering them employment. There were also several industrial thesis project providers that explicitly used master's thesis projects to span the boundary into unfamiliar knowledge areas. This involved relying on students to gather knowledge on, and explain the opportunities of, state-of-the-art research, or have them integrate novel technology into an existing product (Table 2).

4.2. Overcoming the challenges of writing a master's thesis

The first subsection provides results related to the secondary (pattern) coding concerning the challenges of writing a master's thesis in our context. The second subsection provides an analysis of these patterns. Parts of the patterns that have already been described are not repeatedly exemplified, but the associated code is given in parentheses.

4.2.1. Patterns

Many students felt stressed when writing their master's thesis, as they perceived different obstacles to completing their project. Those who offered an overall explanation for their stress specifically pointed to the feeling that they were carrying out two projects – one academic and one industrial. These students had all been offered a thesis project by an industrial thesis project provider that wanted to learn from unknown knowledge areas (**Reason spanning the boundary into an unknown knowledge area**). As the topics for the master's thesis projects were unfamiliar to the industrial thesis project provider, they were often initially unsure about the size of the scope (Table 3).

Two active strategies for dealing with stress were mentioned by the students. One way was to limit the requirements by the thesis project provider that were to be addressed. The other was to continuously align the requirements by both industry and academia in an attempt to satisfy the demands of both parties. Some students felt that this second approach was, at times, probably just as stressful as addressing the demands from both industry and academia separately. More specifically, it was time-consuming, required unstructured, informal technical discussions and relied on the students' ability to keep themselves motivated (Table 4).

Table 2. Examples of reasons for offering a master's thesis project.

Reason prototype	'B1: Yes, it was all very open. We could, to a great extent, handle it as we wanted. We could shape it, but the demand they had was that it would end with a prototype. Or, I think they saw the master thesis as a way to get a physical prototype delivered in exactly this new field.' 'B2: [The industrial thesis project provider] was more interested in getting that kind of [technical component] … to only focus on building a physical [technical component] and try to measure and get an efficiency that matched what they had simulated. That was what they really wanted to get at, and wanted to do.'
Reason employment	'B3: I talked to the boss, who graduated from the Mechatronics track perhaps three years ago. And she said that yes, this is kind of a recruitment … this time, or … it is a way to see … if I fit at [industrial thesis project provider], if I have that consultancy mind-set or whatever it can be called. The personality … ' 'B4: … honestly speaking the demands were not that great, they were rather more interested in finding people to employ in the end.'
Reason spanning the boundary into an unknown knowledge area	'B5: And it was above all another way of future-proofing them, because they see the industry moving in this direction. This is knowledge they feel they need, and which they are not experts in, because it is not in their traditional working area, but the boundaries are getting more and more blurry, what they are doing in ten years and need to interact with … So … No, it has been a clear information gathering effort in this area.'

Table 3. Examples from the two projects pattern.

Two projects	'C1: In the end it was good because both the department and the company agreed on something. I felt that they … of course the initial requirements were fulfilled. The second part that was added to comply with KTH requirements felt a bit forced in the end … I felt that the project could have been better … aimed at something useful to them.'
	'C2: As they had an idea about what they wanted done, I could not shape the master thesis freely, but at the same time they had … it was not a problem [for the industrial thesis project provider] that I did their engineering task and then also answered a research question afterwards.'
Unknown scope	'C1: They were really, really, like super enthusiastic about this first subject they suggested to add that was [unknown knowledge area]. But, when we when we started looking at it, it was huge. So even the CEO said: "No, this isn't like a Master's, it is more like a doctoral thesis, so you can't do this."'

4.2.2. Analysis

Students typically want to satisfy the wishes of both academia and industry during a master's thesis project. An antecedent to this is to understand the requirements on the associated research and engineering tasks. This is often not a problem when an industrial thesis project provider knows the scope of the engineering tasks well (**Reason prototype**), or when these are not as important as having the student on onés premises (**Reason employment**). However, establishing this understanding is difficult when the topic of the master's thesis project is unfamiliar to the industrial thesis project provider (**Reason spanning the boundary into an unknown knowledge area**). A student

Table 4. Examples of dealing with separate requirements from industry and academia.

Handling stress by limiting industrial requirements	'B5: Then, what I could add in regard to building a prototype, I think what it was a very smart move to limit the actual master thesis to more analytical verification of the system … it was a bit tactical to appraise the opportunities for keeping it … well, to keep the scope for the actual master thesis clear. To set a time limit for each task.'
Handling stress by boundary spanning	'D1: It was the actual implementation, that I did not know what I would have time to finish and how much and how large part of the algorithm I have to implement? How much one should demonstrate? That was what stressed me all the time. Because I wanted to finish everything that KTH required, and what the company required … I always tried to align both sides … But I was, well … I was very clear on that I wanted a lot of meetings to align with all the [industrial and academic supervisors] to see: 'Is this what is required? Is this everything that needs to be done to satisfy everyone?' So, I always ran these alignment meetings, with [academic supervisor]: 'Are you sure this is good enough?' And then I for instance got a result I did not expect, and then I had to align again: 'Do you think … is it better to discuss this result that was not expected? Or should I change direction? Change the research question, or what? What is good enough?' And then at the company I tried to also align more at the end, as I got more time for the demonstration, to ask: 'What are the expectations and what should I achieve for the master thesis to be finished?'
	'A1: The communications aspect worked in favour of the thesis. Once the [student's] plan was communicated, once KTH's plan was communicated, once [industrial thesis project provider's] plan was communicated, once all of those were on the table with clear information about the requirements there were no problems.'
Time required for handling stress	'D1: Yes, it was mostly … I asked a lot and then I got answers eventually, it was not that I tried to pull in a particular direction, but rather to ask … certain questions they could not answer, so I had to wait until they had found out the answer.'
Informal discussions to understand requirements	'D2: Tried getting help. There was a lot of good help by [academic supervisor] and then … talking to some other [employees at the industrial thesis project provider]. Yes, really good help from the first group. They were really like: "Why don't you try this angle, let's talk to this guy or try this angle or that angle." Then there was this discussion over lunch with [the industrial supervisor] where he came with some good ideas. Yes, he said a sentence that really got the penny to drop. Then you got it: "Yes, this is what they want."'
Personal motivation	'I: Did you think it was stressful at any point when juggling the requirements from academia and industry? C2: It was … during the start … when I talked to [academic supervisor] about the suggestion and then … it was though getting started I would say. I: And how did you handle that? C2: Well, looking back, I think I … it was a bit mañana, mañana sometimes [laughs], but eventually I sorted it out.'

with strong negotiation skills and enough disregard for the wishes of the industrial thesis project provider can handle this uncertainty by limiting the requirements from industry. This boundary spanning could still amount to a large effort, but the alternative could easily be more arduous. In contrast, if the student is not able to convince the industrial thesis project provider to accept a limited scope up front, then continuous boundary spanning between academia and industry becomes necessary. This is typically a large effort that requires time, opportunities for informal discussions and a highly motivated student.

4.3. The contribution of boundary spanning to the learning of engineering practice

The first subsection provides results related to the secondary (pattern) coding concerning the relationship between boundary spanning and the learning of engineering practice in our context. The second subsection provides an analysis of these patterns.

4.3.1. Patterns

Opportunities for practicing professional engineering skills were mentioned by several of the students. These opportunities were structured according to four different patterns.

(1) A pattern of students having opportunities to reach out and influence the tasks conducted by different employees of the industrial thesis project provider. These cases occurred at industrial thesis project providers with a trusting relationship to the Mechatronics division or student. The thesis projects were strongly tied to the engineering at the firm, either through the reason for the thesis project (**Reason prototype**) or because the thesis project was a continuation of earlier internships (**Trusted through previous internship**). In all these cases the reason that the students had the opportunity to practice their ability to collaborate with other engineers was the need to boundary span to e.g. align requirements or elicit support for their scientific studies, an effort they were all successful at (Table 5).

(2) A pattern of students being immersed in an engineering team at their industrial thesis project provider. This did not involve opportunities to actively influence the engineers in these teams, more that students had a chance to observe their work and seek help from them. These cases almost exclusively occurred at industrial thesis project providers with a trusting relationship to the Mechatronics division. There was one exception, which involved a company with an explicit – and rare – policy of integrating their master's thesis students into their engineering teams. The reasons for the thesis projects were either recruitment (**Reason employment**) or unknown knowledge areas (**Reason spanning the boundary into an unknown knowledge area**). There was little boundary spanning although the students explicitly managed to balance the workload between industry and academia. It is worth noting that there were different reasons for the lack of boundary spanning – some industrial thesis

Table 5. Examples from the collaboration skill pattern.

Collaboration skill opportunity	'E1: Don't do emails, just call people. I: And why was that so efficient in comparison? E1: Because you can get to the point straight away. Like, this is what I want, this is what you want. Ok. How do we meet in the middle?' 'E2: And the thing is, I am meeting these experts, and you kind of get only one shot with them … So, I did two iterations in my thesis, but then that was more or less plan, so I could book two slots with them.'
Successful academia-industry boundary spanning	'E2: What made me persist? I don't know … I mean I really enjoyed … what system architects do, and I had some experience working with a team at KTH. So, I started doing system architecting with them, and that seemed kind of cool. But what I was doing was more hobby level, and this was more professional level. So, I had to bridge that gap, which was good, because now I know.'

project providers did not insist on their requirements being fulfilled, while others left the fulfilment of the academic requirements entirely up to the student (Table 6).

(3) A pattern of the students being pushed by their industrial thesis project providers to develop their own problem-solving skills. These cases occurred at industrial thesis project providers where a trusting relationship to the Mechatronics division or student did *not* exist, and where the reason for the thesis project was the development of a prototype (**Reason prototype**). Furthermore, although the industrial thesis project providers wanted to keep their own and any additional academic requirements separate, the students successfully brought together the firms and faculty from the Mechatronics division to create a shared aim for their thesis projects (**Successful academia-industry boundary spanning**) (Table 7).

(4) There was a pattern of opportunities for learning certain skills that was found in all types of providers and contexts. These involved presenting engineering results and planning engineering work (Table 8).

4.3.2. Analysis

As expected based on the literature discussed in Subsection 2.2, opportunities for learning informal professional skills occurred at industrial thesis project providers with a trusting relationship to the Mechatronics division or student. As expected, these opportunities did not always depend on the master's thesis project being of immediate relevance to the firm's current business: this was a pre-requisite when the skill involved *actively* influencing engineers, but not when the skill related to more *passively* existing in a team.

However, contrary to the discussion in Subsection 2.2, opportunities for learning informal professional skills related to problem-solving did occur when trust was *not* established, *despite* the associated master's thesis projects being of immediate business relevance. These opportunities occurred in this context as long as the students, despite the firms' wishes, successfully negotiated an alignment between industry and academia.

This implies that both a trusting relationship between industry and academia, and a master's thesis project of relevance to a firm's current business, can separately bring about opportunities for learning informal professional skills. However, realising some of these opportunities will depend on the student being an active boundary spanner.

A trusting relationship can provide opportunities to learn informal engineering skills for both active and passive students. Active students can set up a mutual cooperation on engineering tasks of joint interest, which are established by their successful spanning of the boundary between industry and academia. Passive students do not establish such mutual cooperation, but the trusting relationship at least provides opportunities to observe and get occasional support

Table 6. Examples from the teamwork skill pattern.

Teamwork skill opportunity	'F1: But next to them there is the [industrial thesis project provider team] and we perhaps had more to do with them. And they were very happy about the data set we generated, and stuff like that … '
	'F2: And I had colleagues around me at [industrial thesis project provider] who could help with technical problems, which I had to solve to not get stuck for too long. So I thought … yes, that is what I, mean … I had people around me who could help me.'
Student balanced industrial and academic workload	'F3: Yes, I understand. Yes, no, I have … at one stage I decided to trim down the scope to be finished by summer … or just before summer. It was not much of a negotiation, rather it was like I said that, and then the others said: "Ok, then that is how it is."'
	'F4: … Or we had regular meetings with [industrial supervisor] … but it was important that we felt that the work was feasible for us to carry out and … what one could achieve in that time. And then we discussed that, or more analysed it together … '

Table 7. Examples from the problem-solving skill pattern.

Problem-solving skill opportunity	'G1: Yes, they helped me with that too. So, I presented what I got stuck with, and we discussed how one could solve it, and then I had to … They never gave me a straight answer, but rather he … they gave me the answer to "test it". If I had two alternatives that I was thinking about, they never told me "this one is the right one". I: They never said "B", but rather … G1: No, they said "you will have to test it", "now you need to test it". So, they helped me to formulate how to test it, but then they said "now it is up to you". It actually meant I learnt a lot. It was irritating and took longer time, but I learnt a lot, and I appreciated it.'
Provider intended to keep industrial and academic requirements separate	'G2: I could not actually implement [finished product] … I implemented a thing to research … to make a proof-of-concept. There was not enough time to iterate and build the control itself. That was more of a … research on if it was necessary and could be beneficial. I: So, why did you do that? Was that your own thinking, or something required by your supervisor? To discuss that limitation? G2: I think I discussed it with [both industrial thesis provider and academic supervisor]. Like it felt like it made sense, as [the separate deliverables] was kind of the plan first.'

Table 8. Examples from the presentation and planning skill pattern.

Presentation skill opportunity	'A5: Then in the end after the tests were finished, they wanted another presentation about how they could take this further … in other ways than pure research. That is, what companies which could be relevant to contact, for supplies and cooperation and that kind of stuff.'
Planning skill opportunity	'H1: We had regular meetings every week, in which last week's work, problems and the plan going forward was discussed. Partly for the upcoming week, and sometimes in regard to a longer perspective, based on a Gantt schedule covering the whole project.'

from engineers – also providing training in informal professional skills. A master's thesis project's relevance to a firm's current business can also, by itself, provide opportunities for active boundary spanners. This most likely comes about as it forces engineers to adopt an informal mentoring approach in situations: the relevance of the engineering tasks forces their active interest, but the influence by academic requirements and knowledge means that they do not possess all the answers.

Boundary spanning thus provides, but is not a necessary antecedent to, opportunities for informal learning of engineering practice.

It is also worth noting that, as suggested by Subsection 2.2, opportunities for learning formal professional skills do seem to occur in most contexts – regardless of whether a trusting relationship has been established or the engineering task of a master's thesis project is of immediate business relevance.

5. Discussion

This section discusses the studý s contribution to theory, contribution to practice and the most important limitations.

5.1. Contribution to theory

There is a dearth of literature on the transition from engineering education to early career engineer (Trevelyan 2019) and the outcome of placing engineering students in firms during e.g. internships (Hadgraft and Kolmos 2020). This study contributes to these discourses by investigating the boundary spanning between academia and industry during practice-focused master's thesis projects conducted at engineering firms.

The associated theoretical contribution of this study is threefold. Firstly, that the *motivation* of the individual firm for participating in these master's thesis projects is an important, overlooked *antecedent* for enabling opportunities for learning *informal engineering skills*. Secondly, that *different types of motivation* lead to opportunities for learning *qualitatively different informal engineering skills*. Thirdly, that these opportunities require different amounts of effort to *grasp*, as they require more or less *boundary spanning* between industry and academia to realise.

It is worth stressing *informal*, rather than formal, engineering skills in this theoretical contribution, as academia typically struggles to teach students these skills. This implies that the increased use of learning environments is motivated in this case, and that the assumption that students can learn the practice required at R&D firms during these work placements is well-founded also from an engineering perspective. As an example, we know that mentoring relationships with senior engineers are not straight-forward to achieve, but that it is important for early career engineers to work efficiently (Davis, Vinson, and Stevens 2017). Active mentoring is most frequent in situations with little hierarchy and shared responsibility (Davis, Vinson, and Stevens 2017). This matches the only readily apparent cases of mentoring in this study, which involved students and senior engineers who both had a real world stake in the outcome and did not have an established relationship. Arguably, without awareness of this possibility for mentoring this situation would probably not be considered ideal by academic faculty. However, with this awareness the focus can shift to realising this learning opportunity by combining it with a student with good enough boundary spanning capabilities.

Regarding the theory in the theoretical framework, this study primarily has implications for the discourse on the research–teaching nexus. Firstly, different papers have arrived at different conclusions on whether there is any well-formed causal relationships between research and teaching at HEI (Asplund and Grimheden 2019). This study adds another aspect to this relationship, as it shows how the existence of requirements on research can be one of the necessary antecedents to teaching certain engineering skills. Secondly, this study is yet another example in which this relationship can be implicit, and the positive outcome not even actively sought by those involved. It would for instance seem rational to a HEI to only involve firms that are very positive to research in their master's thesis projects, but this study suggests that this might not always be optimal.

5.2. Contribution to practice

It is well known that both academia and industry need to think through why and how students are placed in an industrial context for a prolonged time to ensure academia, industry *and* students benefit from the experience (Edwards et al. 2015c). However, usually both students and academic faculty see professional skill development during work (placements) as mostly independent from academic control and assessment (Bennett, Richardson, and MacKinnon 2016; Edwards et al. 2015a). Many of the suggested reasons for this are centred on academia, students or uncontrollable factors, such as the importance of students taking ownership of their own professional skills development, that academic faculty lacks knowledge about the industrial context, and the uncertainty surrounding the engineering skill set in the future job market (Amiet et al. 2020). In contrast, we know that companies have different motivations for offering long term placements or internships, such as the wish to recruit, get access to additional resources, or tap into state-of-the-art knowledge (Edwards et al. 2015b). This motivation might not be possible to change, but this study suggests that being aware of its influence can allow us to control its implications.

Most, if not all, of the master's students interviewed in this study were satisfied with the opportunity to work with an engineering problem of substantial complexity. Similarly, the examiners of the master's thesis course had accepted both the students' attempts at engineering a solution, and their accompanying scientific studies. By all appearances the students' final leg of the journey towards becoming early career engineers had been successful.

However, only 28 of the students had a substantial opportunity to learn more about any professional skill, and only 10 of these had the opportunity to practice informal professional skills.

Furthermore, some students found it difficult to work with firms that wanted the students to explore knowledge areas on their behalf. As alluded to in the previous subsection, to mitigate these issues requires teachers to:

- Only encourage students who are able and willing to span the boundary between academia and industry to engage with firms that offer master's thesis projects as a way of exploring unknown knowledge areas.
- Encourage students to engage with firms that offer master's thesis projects of immediate relevance to their business, regardless of whether they are able or willing to span the boundary between academia and industry. However, teachers should prepare the students by explaining the benefits of active boundary spanning in their context.
- Actively seek a close working relationship with firms that offer master's thesis projects as a way of recruiting early career engineers. Students who engage with these firms should at least get the opportunity to learn by passively observing engineers at work provided by a trusting relationship between industry and academia.

Arguably, our results also have implications for the hidden curricula (Villanueva et al. 2018) of many higher educational institutions in engineering, as both faculty and engineers often see little value in engineers acquiring research proficiency (Griffiths 2004). We have shown that this attitude can be a barrier to learning informal engineering skills in the studied context, even though these skills are not necessarily related directly to research. Arguably, lowering this barrier could also serve students well in their early engineering career in other ways, as the associated boundary spanning can involve weighing state-of-the-art technology and knowledge against 'engineering as usual'. We know that firms often invest in certain technology and practices to the extent that they become locked to a specific technological trajectory (Dosi 1982). Attempting to alter this trajectory is difficult and will require students to consider both business and technological limitations. While engineering students typically want to focus solely on technology, this boundary spanning is an opportunity to describe the value of their work in terms of e.g. commercial value and sustainability. Many master's programs, including the Swedish engineering master's (The Ministry of Education and Research 1993), intend for this to be a learning outcome. However, there are not always opportunities for it to be learnt. Indeed, many practicing engineers find it difficult to describe their work in such terms (Trevelyan 2019).

5.3. Limitations

This study has two main limitations. Firstly, in regard to theory, practice-focused master's thesis projects placed at firms create a specific learning environment, as academia will have requirements on the output which are not necessarily solved by the successful engineering of a system. Other motivations for work placements, such as capstone courses, might not have as strong academic requirements. It is entirely conceivable that results might differ under these circumstances. We have worded our discussion and conclusions to take this into account. Secondly, in regard to practice, we focus on the learning of professional skills. There are other factors that need to be considered when placing a student in a work environment. As an example, a firm might force a student to sign a non-disclosure agreement and not allow results to be released until the work has reached a certain (production ready) quality. The suggestions put forward in this paper are thus meant to be only part of a teacher's assessment of whether a work placement matches a particular student, rather than absolute guidelines.

We also note that among the 14 students that did not take part in the second round of interviews, 5 did not finish their master's thesis projects. Three of these students were placed at a firm. It is possible that there were unique challenges to the boundary spanning that these students had to perform, which can explain their failure to finish. However, this should not reduce the strength of the observations reported in this study. Furthermore, the associated discussion with the supervisors at the Mechatronics division, described in the methods section, did not indicate the existence of any such unique challenge.

6. Conclusions

The transition from engineering student to early career engineer is often difficult. On the one hand, academic courses become more arduous by teaching increasingly advanced skills. On the other hand, some of the skills that an early career engineer needs to possess are not taught by HEI. Work placements have been suggested as a solution to this by providing a realistic context with opportunities to learn skills that academia is unable to teach. However, the implications on learning outcomes of placing students in an industrial context are understudied. Academic requirements can easily be overlooked if related to skills such as research proficiency, which are often seen as of little value to engineers.

However, this study has found that boundary spanning to align academic and industrial requirements can be valuable during practice-based master's thesis projects conducted at firms. This boundary spanning can better prepare students for an (early) career in engineering by providing opportunities to learn informal professional skills, or even be critical to passing such a course at all. This ultimately depends on the *motivation* of the individual firm for offering the work placement. Specifically, different types of motivation can require a student that is both willing and able to reconcile academic and industrial requirements by actively spanning the boundary between industry and academia. Teachers thus need to consider this motivation carefully when planning and preparing a student for such a work placement. Firstly, to avoid unnecessary difficulties with completing thesis projects, teachers should avoid matching firms interested in investigating new knowledge areas with students that are weak boundary spanners. Secondly, to optimise the opportunities for learning professional engineering skills, especially informal ones, teachers need to explain the need for active boundary spanning in work placements at firms that host master's thesis projects of immediate business relevance. Thirdly, to avoid missed opportunities for learning informal professional engineering skills, teachers should strive to have a trusting relationship with firms that offer master's thesis projects as a way of recruiting early career engineers.

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