Doctoral education in engineering: training for science or industry?

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Conference Key Areas: Engineering Education Research, University-Business cooperation, Engineering Skills

Keywords: doctoral education, engineering science, philosophy of science

1 INTRODUCTION

Doctoral education is commonly characterised as training people in the art of scientific research. In Finnish legislation the aims of postgraduate education are defined as 1) gaining sufficient knowledge and skills for producing new scientific knowledge, 2) becoming conversant with the nature and development of one's own field, 3) gaining such knowledge of science in general and disciplines relating to one's field as to follow developments in them [1]. What knowledge is sufficient and which skills needed for production of new scientific knowledge depends on the discipline. In engineering these topics are not much discussed [2] but some ideas are nevertheless embedded in the doctoral education.

It is, however, also more and more common to expect the doctoral education to provide benefits also to labour market outside academia. Doctoral education is important to companies for three reasons: recruited doctors bring along latest knowledge and problem solving skills for multifaceted problems; doctors in research institutions contribute to research and product development in companies through co-operation networks; and doctoral education can be employed as continuous education to employees not yet holding a doctoral degree [3]. Serving only the needs of scientific community thus seems no longer sufficient for doctoral education. This raises a question of interest in this paper: Are the requirements for doctoral education set by scientific and industrial communities commensurable or competing?

1.1 Concept of engineering science

The online version of Encyclopaedia Britannica does not recognize the entry *engineering science* per se, but places engineering under the heading 'Science' with definition: "Engineering, the application of science to the optimum conversion of the resources of nature to the uses of humankind" [4]. There are several different stances as to what kind of endeavour engineering science is. Engineering science can be seen as natural science [5] , as an applied science [6] or a scientific discipline of its own [7].

There are also different stances as to what engineering science does. Kroes understands engineering science as research studying whether a certain construction fulfils a certain pre-defined criteria [8]. In this definition creating the construction under scrutiny is not part of engineering science research, but a product of process of engineering design. Eekels, on the other hand describes engineering design science as a scientific study of engineering design practice and engineering design methods [9]. Both of these characterizations identify engineering science as a research type of activity and leave engineering design process and end products outside its realm. Hendricks et al. take a different stand to this issue. They suggest that engineering science as an inquiry is not similar to pure or applied science, but that it has a nature of its own. They also suggest that in engineering science the methods are used to provide useful design data rather than to assess a hypothesis. [7.] In their approach engineering science seems to compass both activities, research and design.

1.2 Challenges of doctoral education in engineering

A large survey from year 2006 revealed that Finnish doctoral students in engineering science perceived the theoretical and methodological supervision worse than doctoral students in any other discipline [10]. Another smaller case study identified three challenging areas in doctoral studies in Helsinki University of Technology (currently a part of Aalto university): 1) choosing and using research methods, 2) publishing, and 3) internalising the mode of scientific thinking. The topics were present in both students' and supervisor's views. [11.]

An Irish study investigated the ways on which critical thinking is advanced in university graduate education. It was noted that academics' definitions of critical thinking were much better formed in non-technical disciplines that for example in engineering, with engineering academics' definitions falling more into the 'I know it when I see it' division. [12.] This inability to explicate a concept central to scientific mind set suggests that topics relating to philosophy of science are not explicitly taught to students or discussed during supervision. Also a study by Lahenius and Martinsuo concluded that in engineering doctoral education thinking skills result from indoctrination into the culture of scientific community rather than from actual training [13].

2 EMPIRICAL FINDINGS ON THE NATURE OF ENGINEERING SCIENCE

An empirical study of the nature of engineering science research in Finland supports the view of Hendricks et al. [14]. The study aimed at understanding the prevailing philosophy of engineering science in Finland and strived to comprehend the essence of knowledge and knowledge-creation processes in the field. The subject was studied from the viewpoint of a descriptive philosophy of science, and focused on the nature of knowledge and inquiry processes with the intention of describing them as they are rather than how they should be.

2.1 Data and methods of the study

The data used in the analysis consisted of fifty engineering dissertations from Tampere university of technology (TUT) and the related hundred and fifty evaluation statements. As the purpose of the study was to understand the conception of science as theory-in-use and not as espoused theory, the dissertations were considered to demonstrate the scientific thinking better than interviews or surveys. The study was organised as a case study. The case selection was strategic and based on an view that TUT made a solid critical and paradigmatic case for several reasons. As a university with clear focus on engineering science but many different research areas and engineering disciplines, TUT is a broad but clearly defined prototype of a higher engineering education institute in Finland.

The research process followed the lines of qualitative research and applied the method of qualitative content analysis. Qualitative content analysis was used according the ideas of constructivist-interpretive rather than positivist paradigm. Thus the aim was not to organise qualitative data with quantitative means, but to reduce and display the data in a way that permits conclusion drawing in hermeneutical sense - creating knowledge of the motivation and meaning behind actions. The coding scheme used in the analysis was theory-guided coding, as the concepts related to the inquiry were previously known, but the required selection of concepts along with their relationships was not [15]. So the coding started with a tentative coding scheme, which evolved during the coding process to the final scheme.

In practice the coding of data was executed in six rounds. Counting the frequencies of codes and categories and exploring their distributions in documents and families of documents proved to be the most useful aids for reduction of data and drawing of conclusions. The preconceived sources of differences (faculty, gender, form of dissertation) were examined by comparing the patterns of codes in different groups. Also the five different research profiles identified in the data during the analysis were analysed similarly.

2.2 Results and their general significance

In the study it was discovered that most engineering science research done towards doctoral dissertations can be classified as design science. Design activities were central to the inquiry and research objectives contained aims such as to engineer/construct, to evaluate, to improve, to demonstrate and to determine parameters. In fact forty-three out of fifty dissertations had design-oriented objectives.

Study also revealed that scientific inquiry in engineering usually requires building conceptual and material constructs and developing new methods for analyses, design, implementation or evaluation. It suggests, that engineering science is a predominantly constructive activity, but aims at finding more general solutions compared to engineering, which aims at more particular solutions to technical problems.

In addition to different objectives and different process of inquiry compared with pure or applied science, also rest of the disciplinary matrix of engineering science becomes rather unique as suggested by Hendricks et al. [7]. Theory does not usually provide a hypothesis to be tested, but provides understanding of the problem at hand and about tools usable for problem-solving. Methods are more fundamental than theory and used to provide useful design data rather than evidence or proof in favour or against a hypothesis. Values reflect the pragmatic concept of truth with utility as the most important and employed norm in evaluation the quality of the research work.

However, the philosophy and conception of design science was quite rarely explicated in the dissertations. In fact, relating one's research to any kind of philosophical or methodological framework was rather uncommon. Epistemological and ontological assumptions were discussed and justified if they followed some tradition other than positivistic one and were more often explicit if the inquiry directly included the human interface of some kind. Yet, a better description of methods and more logical presentation of work were often required in the evaluation statements.

3 IMPLICATIONS OF FINDINGS TO DOCTORAL EDUCATION

All this suggests that also the doctoral level inquiry in engineering science seems to be perceived more as technical than scientific problem solving and described and discussed accordingly. This is likely to serve better the interests of industry - which is usually more interested in new technical applications in comparison to pure knowledge - than the interests of science. The noted lack of language to conceptualise engineering science research is most likely connected with the view, probably as both, cause and a consequence. It is also likely to contribute strongly to the deficiencies identified in doctoral education and supervision in engineering science.

3.1 The dual nature of scientific problems in engineering

Technical problem solving and scientific inquiry can have similar objectives and can even employ similar methods, but as processes they are not the same. In simplest case, illustrated in *Fig. 1*, the connections between the two processes are quite clear, although some parts of the scientific inquiry, namely the evaluation and explication of contributions, are not always presented in scientific reporting such as dissertations [14]. The interrelation between the two becomes more problematic, if for example the technical solution to the problem at hand cannot be found as illustrated in *Fig. 2.* This does not have to mean, that no interesting new scientific knowledge is created, but the relevance of the results depend on the way the scientific objectives are set.

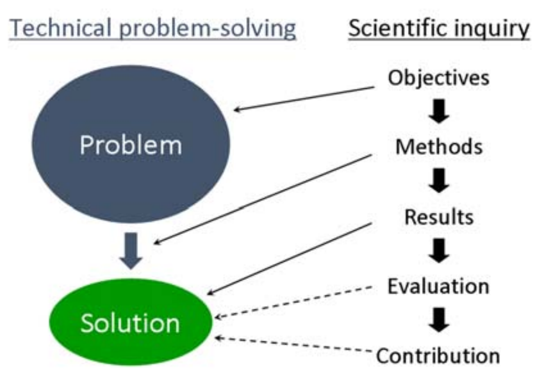

Fig.1. Simple relationship between technical problem solving and scientific inquiry

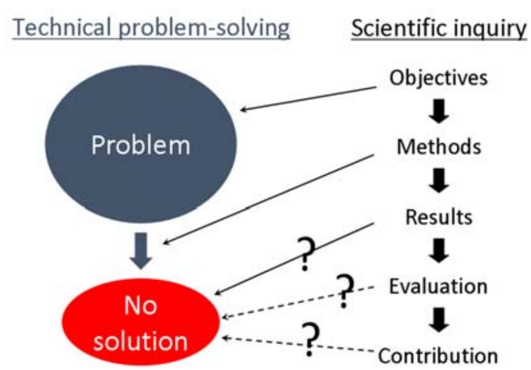

Fig. 2. More complicated relationship between technical problem solving and scientific inquiry

The story becomes even more complicated once we move to other scenarios typical for technical problem solving. Three of the various possible processes are presented in *Fig. 3*. Now it becomes even more challenging to see and describe the process in terms of the scientific inquiry.

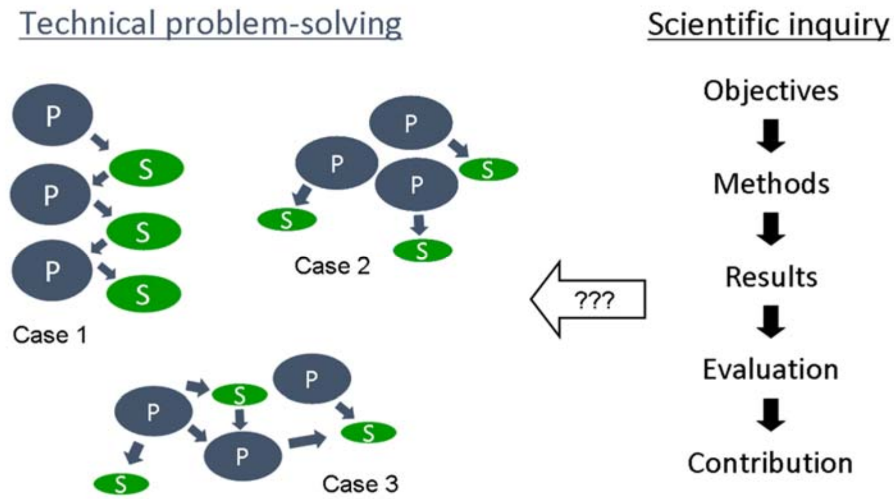

Fig. 3. Relationship between cases of multi-phased and non-linear technical problem solving and scientific inquiry

Equating engineering science inquiry with high intelligence technical problem solving may fulfil sufficiently the needs of industry, but it unnecessarily narrows down the scope of academic community. A failure to find a technical solution can be a source of valuable knowledge, or an unsatisfactory solution to one technical problem can provide a solution to entirely different problem than the original one. Focusing on the problem-solving side can also lead to situation, where the evaluation of the quality of inquiry with respect to aspects like truth-value, applicability, consistency, neutrality and utility is deemed unnecessary, as researchers are satisfied with a local solution of a problem. This can weaken the cumulating, self-correcting and advancing nature of scientific knowledge within the discipline.

Yet, focusing only on the science - especially if the design of new mental or physical constructions is excluded from the science - could lead us to a situation, where the benefits for the industry would weaken. If academics concentrate on testing the viability of solutions created in industry or studying the methods or processes used in creating those solutions, it could well be that the most innovative and further reaching new kinds of solutions would not be arrived at all. As creating that kind of solutions takes a lot of time and effort and entails also a possibility of yielding nothing, it may well be far too risky for commercial actors to carry out that kind of endeavours.

Seeing engineering science inquiry more clearly as project with certain technical objectives and related, but different, scientific objectives has potential to benefit both industry and academia. Clearly stated objectives are usually more likely to be met than the unclear ones. Looking for local solutions but simultaneously keeping an eye on the global possibilities and larger value of the produced knowledge would not only advance both realms, industry and academia, at the same go, but could help in discovery of totally new interrelated business and research areas and ideas and innovation leaps in addition to the incremental development.

3.2 Development needs in doctoral education

Taking the dual nature of engineering science problems into account in doctoral education necessitates some changes in Finnish post-graduate training. A more thorough elaboration of the following suggestions can be found in [14]. First it requires building systematic training in the philosophy of engineering science and engineering science methodology for all doctoral students. The training should introduce the ideas of design science and give students the language and vocabulary to describe the whole process of scientific inquiry. It should also help them to relate the inquiry process to the technical problem they are dealing with, in order to be able to articulate appropriately the objectives of both technical problem solving and scientific inquiry and plan the rest of their work accordingly.

Along with the training also supervision concerning the similar issues needs to be increased and improved. This requires giving more support to the supervisors. As they already are experts in scientific research, organising peer support is a good option. Although this could take place through professional discussion, for example during coffee breaks, reserving a special time an place for discussions is expected to be beneficial as dealing with these kind of issues requires certain amount of concentration.

Systematic training and discussions within institutions provide a good base for discussion at a national level. Taking the discussion to a national level could help in getting also other stakeholders, such as companies and research institutes, involved in the conversation. This kind of discussion would have great potential to advance the co-operation between academia and industry also in other identified areas of interest.

4 CONCLUSIONS

This paper aimed at answering the question: Are the requirements for doctoral education set by scientific and industrial communities commensurable or competing? Although the primary aim of doctoral education is to supply doctoral candidates with sufficient knowledge and skills to produce new scientific knowledge, it seems that engineering science inquiry is often perceived as technical rather than scientific problem solving and described and discussed accordingly. This is likely to serve the needs of industry on the expense of scientific community.

An empirical study of the nature of engineering science research in Finland observed the strong design science -oriented nature of engineering science. It also confirmed the earlier noted lack of language to describe and discuss the philosophic grounds and commitments of engineering science. The dual nature of engineering science problems - the intertwining of technical and scientific problem-solving processes - implies that the better the both processes and their interrelations are understood and described, the better the end result in both technical and scientific sense.

Sufficient understanding and explication of the scientific side of the engineering science inquiry does not take away the technical challenges of the research problems. On the contrary, recognizing the framework of the inquiry as e.g. design science and following its principles instead of trial and error method, brings more systemacy and efficiency also to the technical problem solving.

Thus not addressing the different requirements and not talking about the different sides of inquiry can lead to a situation where interests seem to be competing. However, recognising the dual nature of the problems and providing doctoral candidates with sufficient language and skills to address openly both processes, technical problem-solving and scientific inquiry, can help the processes to reinforce each other and make the requirements commensurable. This way the doctoral education in engineering would mean training for science and industry.

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