Structural Development of Substance in Engineering Education: Method of Cornerstones

Abstract—**During the current millennium, engineering education has confronted an emerging problem with learning. Driving forces have mainly been economical, since financial pressure and effort for increasing efficiency have given rise to growing amount of accessed and graduated students. Consequently, in the lack of time and financial resources, universities have had a tendency to decrease the emphasis on thorough and time-consuming learning of fundamentals. As a result, so called immediate skills have gained excessive role in comparison with long-term skills in engineering education. According to a generally accepted view, students learn to carry out engineering tasks quite well, but they do not necessarily learn to think. Recently, a study carried out at MIT ended up to call for "coherent and interconnected curriculum structure" to achieve excellence in engineering education. We suggest that by utilizing the hierarchical structure of natural sciences in engineering education, such a coherent and interconnected structure can be created. In this paper, we show how the method of cornerstones is implemented to clarify engineering substance and to promote higher learning. By making cornerstone-based structure visible to students, we aim to clarify and harmonize the substance and to promote both immediate and long-term engineering skills.**

Keywords—engineering education, higher learning, method of cornerstones

I. Introduction

During the economic pressure of current millennium, a global worry about the lack of higher learning in higher engineering education has arisen [1], [2], [3]. According to largely accepted view, students learn to carry out engineering tasks quite well, but they do not necessarily learn to think. One the most famous advocates of such ideas is Derek Bok, a former president of Harvard University [4], [5]. In engineering, the roots of higher learning mainly evolve from thorough understanding of fundamentals, and consequently, from the ability of exploiting abstractions to tackle tangible problems. Furthermore, recent study from MIT concluded that achieving excellence in engineering education calls for “a coherent and interconnected curriculum structure” [6]. In this paper, we promote higher learning by suggesting a coherent method for structural development of substance in engineering education.

The balance between immediate and long-term skills is an endless dilemma in engineering education. In order to offer students important engineering skills appreciated in various tasks of industry, the toolbox of an engineer is filled with different designing tools, rules, standards and measurement procedures. These mainly constitute immediate skills in engineering education. They are certainly important, but they also have a downside: their validity may expire over the technological development. In order to also gain more profound understanding and readiness for changes in rapidly evolving industry, careful and time-consuming learning of fundamentals is required. These mainly constitute long-term engineering skills, or even permanent engineering skills, since their feasibility is not affected by the changes of technology. According to generally accepted view, the development of immediate skills in engineering education has quite successfully followed the changes in technology during the recent decades. However, we suggest that this has not been the case with long-term engineering skills. Especially in the economic pressure of current millennium, engineering education has excessively tilted towards immediate skills. Hence, we suggest that changes in engineering curriculum have not promoted a sustainable development of long-term skills during the most recent decades.

Recently, we presented the principles of a method to promote higher learning in higher engineering education [7]. In addition, as a case study, we have also shown how the method of cornerstones is implemented to clarify and to deepen the learning of circuit analysis in electrical engineering [8]. In this paper, we take a more general view on the subject to develop the whole field of engineering education by means of method of cornerstones.

II. Method of Cornerstones

A. Background

In order to have a systematic way to promote higher learning in engineering education despite the economic pressure, the method of cornerstones was created. In fact, the goal is twofold: 1) to clarify the content of immediate engineering skills, and 2) to give students a clear view towards deeper comprehension and long-term engineering skills. The method is enabled by hierarchical structure of natural sciences, since the fundamental rules of modelling on a certain level of concretization are only made up from the ones on the lower level of higher generality. Immediate engineering skills mainly arise from the identification and utilization of these fundamental rules. This gives a great opportunity to clarify the substance in engineering education. Furthermore, long-term engineering skills are closely related to understanding the assumptions validating the fundamental rules on a certain level of concretization. We will clarify these ideas in the following chapters.

According to our experience, some fields of engineering have already drifted quite far away from their roots. To be precise, in some specific and narrow fields of engineering, even professionals do not necessarily know where their models originate from. Thus, they are not aware about the concretization of the models they are using. As a consequence, harmful shortcuts in education may come out. Although these are only cautionary examples, yet they make us worried about such progress becoming more common. Luckily, these problems can be avoided by recognizing the concretizations and identifying the cornerstones of modelling.

B. Implementation of cornerstones on engineering education

The method of cornerstones rises from the hierarchical nature of science, figure 1. Although the all-encompassing theoretical framework of physics, the theory of everything, still remains incomplete, it inevitably seems that all the fields of engineering fundamentally rise from the same foundation. In fact, the recent discovery of gravitational waves is yet another step towards the final goal [9]. As we approach the theory of everything in any field of engineering, generality increases. And as a consequence, different fields of engineering resemble each other more and more. The circles in figure 1 represent different levels of modelling, or more precisely, different levels of concretization. When we recede from the theory of everything, level of concretization increases, since more and more details get fixed. And at the same time, generality decreases. Each level of concretization includes a set of fundamental rules of modelling, which we call cornerstones. They are marked with dots in figure 1. Thus, each level of concretization has a set cornerstones, which lay the foundation for modelling there.

The fundamental educational idea in the method of cornerstones is to make the structure of figure 1 visible to students. Then, this structure will be utilized in education by positioning courses on this road map of engineering substance. This is the main idea behind the coherent and interconnected curriculum structure that we are trying to build with the method of cornerstones.

C. Clarification of immediate engineering skills

To make things more concrete, let's look at an example course of engineering, figure 2. In engineering education, we are always located on a certain level of concretization, and

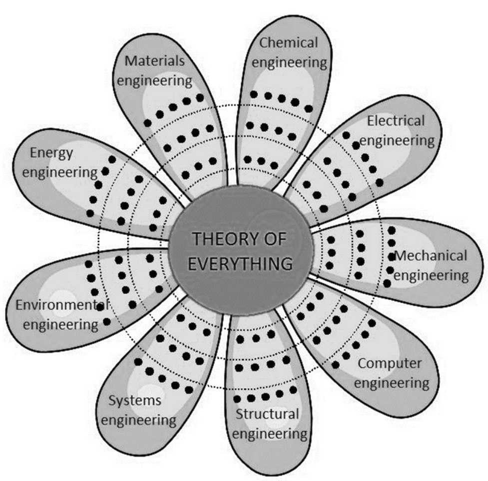

Fig. 1. Hierarchical structure of natural sciences.

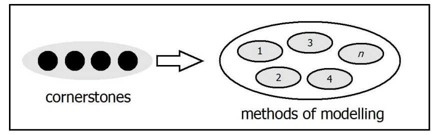

Fig. 2. Structure of one example course.

consequently, we always possess a certain set of cornerstones. Typically, the substance of an engineering course comprises different methods of modelling, which are utilized in real-life problems. Thus, from this point of view, figure 2 can be thought to represent a typical and maybe a bit simplified substance for a single course in engineering education.

Since the emphasis of engineering is on getting devices and systems to run, it is important that engineering degrees include a fair amount of immediate tools. They are highly appreciated in versatile tasks of industry, and due to them, engineers possess extensive toolboxes to solve many kinds of engineering problems. Usually, immediate engineering skills mostly arise from the ability to utilize different methods of modelling. These important contents of engineering toolboxes are depicted in the right side of figure 2.

But how do we clarify immediate engineering skills by means of the methods of cornerstones? The answer lies in identifying the cornerstones on each level of concretization. It is important to understand that different methods of modelling only rarely represent independent rules. Instead, they should rather be considered as different ways to apply the same cornerstones. In this way students are given a possibility to realize how different methods of modelling originate from the cornerstones. Consequently, after identifying the cornerstones and realizing the foundation of different methods of modelling, students are given much clearer overall picture of the engineering substance in question.

Figure 3 presents a concrete example of clarifying immediate engineering skills by means of cornerstones. This example is from electrical engineering, since figure 3 represents the house of resistive dc circuits. It stands on three cornerstones, and it includes many different methods of modelling. After the

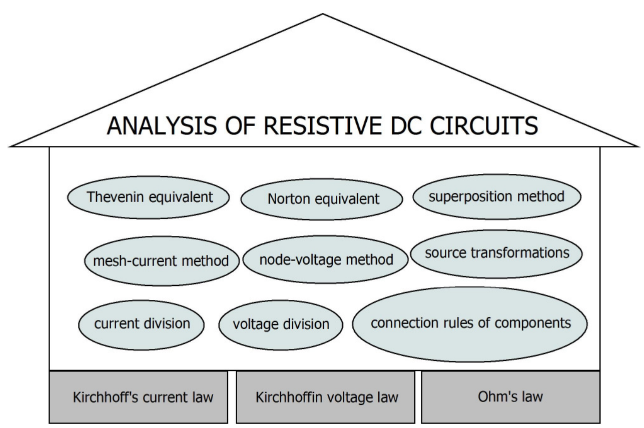

Fig. 3. Cornerstones and methods of modelling in resistive circuit analysis.

implementation of this course in technical university, a common personal feedback from students used to be often dealing with the confusion related to a great amount of different methods to analyze electric circuits. According to students, benefits of different methods easily remain unclear, and it is often difficult to see, which method is the most suitable for a certain circuit. However, by utilizing the idea of cornerstones the problem of multiple methods dissipates, since all the different methods arise from the same cornerstones. Thus, all the different methods can just be seen as different ways to apply the same cornerstones. In this way, students are given an opportunity to understand that the justification of existence of different methods mainly comes from finding the most efficient way (the smallest number of equations) to solve the problem. This is the idea in clarifying the content of immediate engineering skills by means of the method of cornerstones. First the cornerstones are recognized, and then, different methods of modelling, which usually comprise immediate engineering skills, are derived from the cornerstones.

D. Promoting higher learning and long-term engineering skills

Learning of immediate engineering skills typically occurs without questioning the validity of cornerstones. As repetition and routine are important means in learning to effectively utilize different methods of modelling, cornerstones are then usually taken as unquestioned rules. However, if we want to promote higher learning and long-term engineering skills, the validity of cornerstones has to be questioned.

Majority of long-term engineering skills arises from a thorough comprehension of fundamentals. Consequently, in the pursue of higher learning, we need to look underneath the cornerstones. Then, instead of unquestioned rules, cornerstones are seen as testable properties. That is, we try to give students an impression about the assumptions validating the cornerstones. And this is where the role of a teacher becomes especially important, since we need to look at more general levels of concretization, which typically are unknown or even frightening to students. Thus, a teacher has to be able to use a familiar language while introducing the topics on the lower level of concretization. Usually a mathematical representation is not a familiar one. Hence, in order to give students a clear impression about the assumptions validating the cornerstones, deeper content knowledge of a teacher is called for.

A concrete example of the assumptions validating the cornerstones can be seen in figure 4, which presents two levels of concretization in electrical engineering. The higher level in figure 4 represents the same substance as resistive dc circuit analysis in figure 3. As already mentioned, when learning immediate engineering skills related to different methods of modelling, cornerstones are typically taken as unquestioned rules. However, in order to understand the restrictions behind these methods of modelling, we have to treat the cornerstones as testable properties. Thus, we need to understand how the three cornerstones of resistive dc circuit analysis in figure 4 are derived from the five cornerstones of more general level of

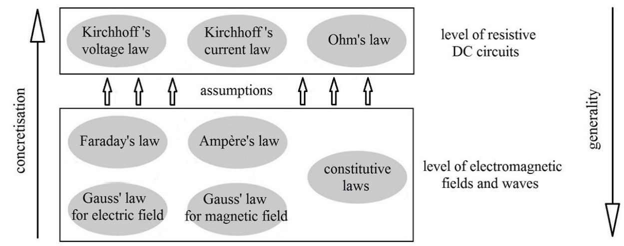

Fig. 4. Cornerstones of modelling on two levels of concretization in electrical engineering: cornerstones on higher level of concretization can always be derived from the ones on lower level.

concretization. For example, in figure 4 Kirchhoff's voltage law (a cornerstone on the higher level) is based on Faraday's law (a cornerstone on the lower level) with the assumption that the magnetic flux density through a closed loop does not vary with time. We are not going into more details of deriving the cornerstones in this paper, but instead, we only want to emphasize that this kind of fundamental understanding mostly comprises long-term engineering skills.

III. COHERENT AND INTERCONNECTED CURRICULUM STRUCTURE IN ENGINEERING EDUCATION

In a recent study carried out at Massachusetts Institute of Technology, Dr Graham ended up to conclude that "excellence in engineering education calls for coherent and interconnected curriculum structure" [6]. In this paper, we suggest that by extensively utilizing the method of cornerstones, such curriculum structure can be created.

As depicted in figure 1, in principle all the fields of engineering have the same kind of structure. However, as the theory of everything still remains incomplete, the strengths of fundamental theories behind different fields of engineering vary. For example, electrical and mechanical engineering are the ones with the strong fundamental theory. On the other hand, for example the fields related to biological engineering do not have equally strong fundamental theory, since science of today is not yet able to unambiguously model living organisms. However, the lack of strong fundamental theory doesn't necessarily significantly hinder the utilization of method of cornerstones. Instead, it may provide a transparent method to organize the substance and to recognize the shortages of unambiguous modelling.

A principal and simplified structure of a single field of engineering is presented in figure 5. In this example, there are four different levels of concretization, and this structure could represent for example the electricity-related substance in the Master of Science degree of electric power engineering. Then, the lowest level of concretization would be the level of electromagnetic fields and waves, which was already presented in figure 4. Furthermore, as the level of concretization increases, there are different levels of circuit analysis, since the specialized models of electric power engineering are mostly based on circuits. The lowest levels of concretization in circuit analysis typically represent the modelling of circuit transients, and as concretization further increases, we are dealing with sinusoidal steady-state circuit analysis. The uppermost level of

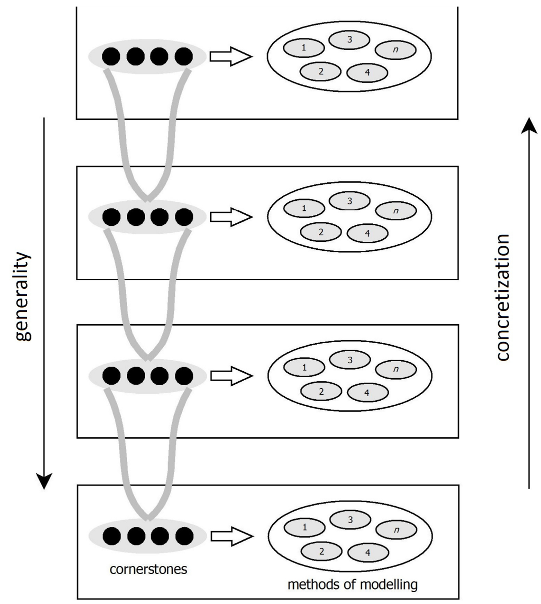

Fig. 5. Principal and simplified structure of a single field of engineering.

concretization could represent some narrow-field models of specialized studies, where more and more details get fixed. However, regardless of the number of levels, the most important idea in figure 5 is that all the substance related to electrical engineering can be positioned on this road map.

The structure presented in figure 5 repeats the more general one presented in figure 1. On each level of concretization, immediate engineering skills mostly arise from the ability to utilize different methods of modelling. And furthermore, long-term engineering skills are mostly achieved by understanding, how the cornerstones arise from the ones on a more general level. This is also depicted in figure 5: cornerstones on the higher level of concretization can be derived from the ones on the lower level.

The fundamental idea in creating coherent and interconnected curriculum structure by means of the method of cornerstones is (1) to make the structure in figure 5 visible to students and (2) to position each course of engineering substance on this road map. We suggest that when substance of engineering education is organized in this way, students are able to get a clear and profound overall picture of the engineering field. Furthermore, the road map gives students a clear view towards deeper comprehension. For example, if some specific method of modelling gives significantly different results than the measured ones, problem probably lies in the assumptions validating the cornerstones.

By further extending the application of method of cornerstones, we end up to a structure presented in figure 6. As already mentioned, although the strengths of fundamental theories behind different fields of engineering vary, the same kind of a structure can still be found in any field of engineering. We suggest that by utilizing this structure in engineering education, we finally end up to have a coherent and interconnected curriculum structure, such as Dr Graham recently called for.

The structure presented in figure 6 would offer great advantages for students, but also for teachers. For example, when students are studying secondary subjects of their engineering degree, they would confront the same kind of structure as in their major subject. They would learn what are the cornerstones in other fields of engineering, and due to the coherent and interconnected structure, they would attain quite extensive overall picture of engineering fields. In fact, actual interconnectivity comes from understanding that different fields of engineering resemble each other more and more, as we move towards lower and lower levels of concretization. As an example from electrical engineering, it is not really possible to understand other fields of engineering by means of circuit analysis. But if we understand more general level of electromagnetic fields and waves, it will already give quite good premises to understand for example mechanical engineering.

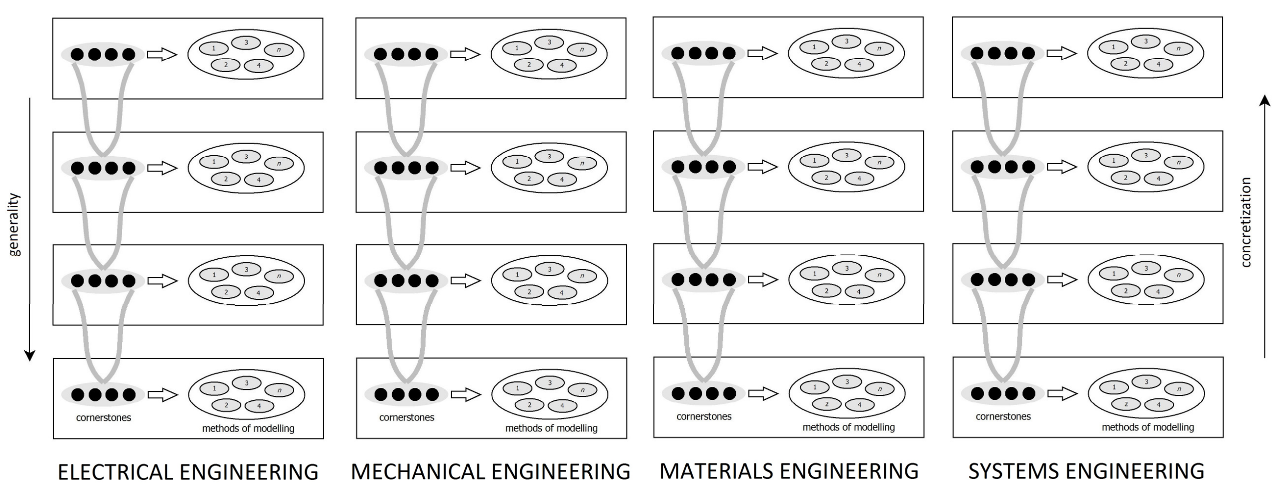

Fig. 6. Principal struture of substance in different fields of engineering

If the substance of engineering education is arranged according to the principles presented in figure 6, we suggest that the coherent and interconnected structure demanded by Dr Graham will be achieved. Although a comprehensive road map including all the fields of engineering is probably unattainable at the moment, even incompleteness of the map doesn't erase its benefits. Instead, it promotes openness and transparency.

IV. Discussion

The dilemma between immediate and long-term skills in engineering education is more or less endless. Immediate engineering skills are highly valuable, since the emphasis of engineering is on getting devices and systems to run. On the other hand, it is clear that competitive R&D cannot rely only on immediate engineering skills. Instead, a more profound approach and long-term engineering skills are also required. In addition, since the validity of some immediate engineering skills may expire over the technological development, long-term skills offer readiness for changes in rapidly evolving industry. With the method of cornerstones, we aim to clarify the interconnected roles of immediate and long-term engineering skills. By drawing a comprehensive road map of a specific field of engineering, students are given an opportunity to get a clear view about the substance. Each level of concretization has its own cornerstones, from which different methods of modelling, and thus the majority of immediate engineering skills, are built from. Furthermore, long-term engineering skills mostly arise from looking underneath the cornerstones and understanding their premises. Then, instead of unquestioned rules, cornerstones are seen as testable properties. This kind of substance-oriented approach also enables a transparent development of engineering education, since all the engineering substance can be positioned on the road map. We suggest that there are no shortcuts in achieving deeper comprehension. And as a result of utilizing the method of cornerstones in engineering education, we might really get graduates that, with the description of Derek Bok, have "learned to think" [4].

In Finland, in the city of Tampere, a nationally exceptional project called Tampere3 is carried out at the moment. The idea is to form a union of three independent universities in the town. As such, a project to join universities is not a unique one, but the exceptionality of Tampere3 rises from the fact that a university of applied sciences is also involved. The goal is to combine Tampere University, Tampere University of Technology and Tampere University of Applied Sciences into one wide-ranging university and to offer students exceptionally wide opportunities for studying.

In this paper, we will not discuss Tampere3 project any further. However, an interesting detail is that the method of cornerstones has been chosen as one educational development pilot in the project. In the first phase this means that the method of cornerstones will be utilized, when the substances of electrical engineering in Tampere University of Applied Sciences (Bachelor of Engineering) and Tampere University of Technology (Master of Science) will be thoroughly scrutinized. The first aim is to draw a detailed substance road map of electrical engineering. Then, each course of electrical engineering from both universities will be positioned on the map. By means of method of cornerstones, we aim to carry out a substance-oriented union of electrical engineering education in Tampere3 project.

In Finland, the scientific subjects, such as mathematics and physics, are at the moment so unpopular among young people that some kind of national concern has already risen. In general, youths find these subjects so difficult already in elementary school and later in high school that the beauty of scientific subjects never really reveals to the majority of pupils. We suggest that also the popularity of scientific subjects could be promoted with the method of cornerstones. When the same road map with the same cornerstones is utilized from the scratch of scientific studies in elementary school, the whole field of engineering doesn't anymore appear messy and frightening. Instead, in the best case, it appears fascinating and logical.

Finally, the method of cornerstones also enables a systematic and transparent tool for continuous development of substance-related proficiency. This is especially useful for teachers, since drawing of unambiguous road map is not easy at all, not in any field of engineering. But during the years the missing connections between the cornerstones of different levels probably complete, at least partly, and as a consequence, a teacher has a stronger and stronger foundation to teach the substance. In the end, it has to be remembered that the individual development of proficiency in natural sciences is always an endless process.

V. Conclusions

In this paper, by means of the method of cornerstones, we aimed to present a coherent and interconnected curriculum structure in engineering education. The method is enabled by hierarchical characteristics of natural sciences, since the cornerstones of modelling on a certain level of concretization only arise from the ones on a lower level. The initial goal was two-fold: 1) to clarify the content of immediate engineering skills, and 2) to give students a clear view towards deeper comprehension and long-term engineering skills. Immediate engineering skills are promoted by recognizing the cornerstones on each level of concretization, and by applying the cornerstones to build different methods of modelling. Long-term engineering skills mainly arise from looking underneath the cornerstones on a certain level of concretization. Then, instead of unquestioned rules, they are seen as testable properties. Thus, in order to gain more profound understanding, we need to understand the assumptions validating the cornerstones. In this way, students are offered better premises for higher learning and long-term engineering skills.

In this paper, the building of coherent and interconnected curriculum structure was started by recognizing the cornerstones on a single level of concretization. Then, the cornerstones were used to build different methods of modelling. Next, different levels of concretization in a single field of engineering were recognized. In fact, after recognizing the different levels of concretization, a comprehensive road map of one engineering field arises from finding the connections between the cornerstones of different levels of concretization. This structure is unambiguous only in some fields of engineering, but still, we suggest that this problem doesn't significantly hinder the utilization of the method of cornerstones in engineering education. Regardless of the field of engineering, the idea is to present the substance as organized and interconnected as possible in order to give students better opportunities to achieve substance-related excellence in engineering. The final goal is to have a comprehensive road map of engineering that can be utilized in every level of academy; from elementary school to university. Furthermore, the method of cornerstones also enables a systematic and transparent tool for continuous development of substance-related proficiency. This is especially useful for teachers, who continuously develop the substance of their courses year by year.

As a long-term goal, we aim to develop and to promote scientific subjects in Finnish academies. The first step is to utilize the method of cornerstones in Finnish Tampere3 project, where one wide-ranging university is combined from three independent universities in Tampere. The method of cornerstones has been chosen as one educational development pilot to organize the substance of electrical engineering for new university.

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