PER NORSTRÖM

3. THE NATURE OF PRE-UNIVERSITY ENGINEERING EDUCATION

INTRODUCTION

The nature of pre-university engineering education is a complex expression, as both ‘nature’ and ‘engineering’ are controversial terms. In this context, *nature* means something like an essence, a purpose, and a set of defining (or at least typical) characteristics. For a subject in school, its nature can largely be captured by answering the following questions: *What* should pupils learn? *Why* should they learn it? *How* should the education be organised for the learning to take place?

This chapter is based mainly on curricula and policy documents. Therefore, the ‘how’ question is not as prominent as the other two. ‘How’ is a matter of method, and is in most cases solved by individual teachers, teacher educators, and textbook authors rather than on the curriculum level. That said, there are strong implications and implicit recommendations in numerous curricula and policy documents, as will be seen later, and some examples from textbooks and research about teaching practice have been taken into account.

Engineering concerns the design and manufacture of technical artefacts, and the term is mainly used when professional engineers are involved (see Marc de Vries’ chapter in this book). Details about its core characteristics, as well as its delimitation from other human activities have been discussed by philosophers, sociologists, and historians of technology during the last decades, and no definition that is generally agreed upon in every detail exists. It is a broad concept, and the contents of pre-university engineering education can thus vary considerably.

Koen (1985, p. 10) described ‘the engineering method’ as ‘the strategy for causing the best change in a poorly understood or uncertain situation within the available resources.’ This ties in well with the experiences of many engineers: the customer or client commonly has vague or even incorrect ideas about what the problem is and/or what needs to be done. Therefore, the first phase of the engineer’s work often consists of figuring this out and it often needs to be re-negotiated during the work process (e.g. Vinck, 2003). Another important aspect of Koen’s definition is ‘the best change’. What constitutes ‘the best change’ is clearly context dependent. Best for whom? What is best for the customer is not always best for the engineer. What is best for the operator is not necessarily what is best for maintenance personnel. There are many possible solutions to a given engineering problem—for a problem of sufficient complexity and/or generality there are incredibly many. The engineer must

M. J. de Vries et al. (Eds.), Pre-university Engineering Education, 27–46.

strive to find the solution that causes the 'best change' given all kinds of restrictions: functional, temporal, economical, aesthetical, legal, etc. Therefore, engineering cannot be merely a problem solving activity, but also one of decision-making (Kroes, 2012; Vermaas et al., 2011).

Engineering activities and engineering skills are about (or are closely related to) creation and creativity. The quality of an engineering design process depends on its result (product or process) and the amount of resources (economical, temporal, material, …) that were used. This is commonly referred to as its *effectiveness* and its *efficiency* (Franssen & Bucciarelli, 2004; Kroes, 2012). To move a large stone by dragging it on the ground can be an effective method. So can moving it by putting it on a cart. But using the cart is more efficient as it demands less force, less time, and fewer people involved. As part of an engineering process, using the cart would therefore in most cases be regarded as a superior method.

Compared with 'nature' and 'engineering', 'pre-university … education' is fairly easy to decipher. By education we mean activities and processes intended to aid learning, mainly in schools and similar institutions. In this article, we limit it to schools. 'Pre-university' means simply that it takes place before university, and may prepare for university. Trying to apply this to a wide range of countries can be difficult, as the role of universities varies slightly. What is studied at university level in one country can be studied at a polytechnic or *Fachhochschule* in another. For the purpose of this article, those differences are not really interesting. The main focus is compulsory schooling attended by children and adolescents until their late teens, guided by a prescriptive curriculum laid down by some state authority or similar body.

The Engineering Design Process

At the heart of engineering is the engineering design process (also known as the product development process)—the process of creating a product that can be of use or causing the 'best change' (Koen, 1985) by implementing the 'intended function, economics of operation or safety to life and property' (as put by ECPD, 1947). Throughout the years, there have been numerous attempts to describe such processes and to prescribe how they should take place. A typical, classical model of an engineering design process looks something like the one in Figure 1. This type of process can be found in many engineering textbooks. The contents are general, the design processes tend to look almost the same no matter if they are about software engineering, electronics design, or mechanical engineering.

The process starts with some kind of demand or wish. From these wishes, a requirement specification is designed; the wishes and needs are formalised as a list of evaluable requirements. Based on this list, a few conceptual design solutions are produced. The suggested design solutions are evaluated and the best one is picked. The best solution is implemented in a prototype that is tested, and modified if

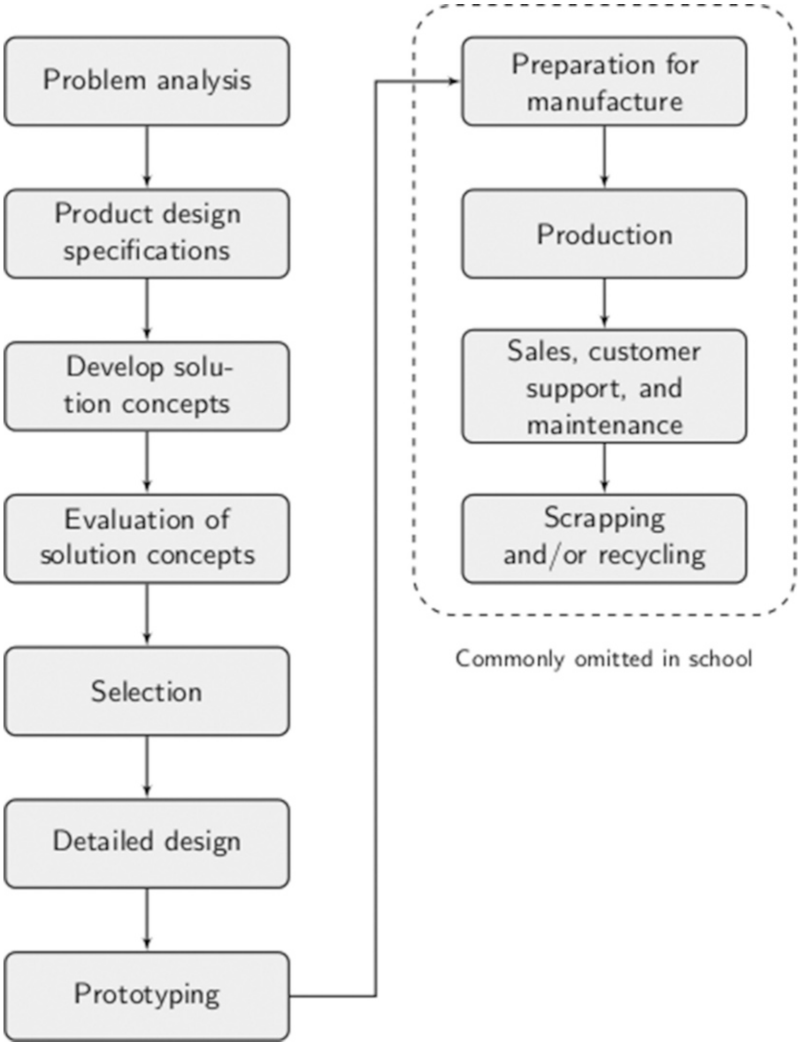

Figure 1. Block chart of a linear engineering design process. Similar charts can be found in hundreds of books and articles, e.g. Denayer et al. (2003). School engineering projects commonly end with prototyping

necessary. Based on the prototype, the final product is designed, and manufacturing can start. After manufacturing and delivery, the product enters a phase of service and maintenance, and when worn out it has to be recycled or scrapped in an environmentally friendly way.

This kind of naïve descriptions of an idealised engineering design process fits well with a functionally organised company. The marketing department collects needs and wishes from existing and potential customers and leave them to a senior design engineer. The senior design engineer writes the specification and leaves it to the junior design engineers. They produce drawings, circuit diagrams or similar documents which they leave to the manufacturing unit. And so on. After having done one's duty, the product is never seen again. Somewhat jokingly, it has been called 'over the wall engineering'—when you have finished your part you throw it over the wall to the next in line and never see or hear about it again (Eppinger et al., 1994). It is a linear process from wish or need, via design, manufacturing and use, to recycling. You never turn back.

That these idealised models do not always work perfectly is well known. If a designer is not an expert in manufacturing methods s/he can accidently design a product that is not feasible to produce, for example. In those cases, the smooth, linear model of development must be modified and another iteration of the design phase be allowed. It can also happen that customers change their preferences during the months or years that pass while the product is developed. If there is no way to change the requirements during the process, the company will end up with unwanted products. Because of reasons like these, there have been strong objections to the linear model of engineering design, and especially since the 1990s many alternatives have been suggested. One such category of design models are called *concurrent engineering*, and use multi-disciplinary teams so that e.g. manufacturability and maintainability can be built into the design already from the beginning (Eppinger et al., 1994). Another group of design process models are called *agile methods*. They were first used in software development projects and are characterised by customers' taking part in the project all the way through, many deliveries of functioning sub-systems, and flexibility concerning the change of requirements and design specifications. Well-known examples include *Extreme programming* and *Scrum*.[1]

Non-linear development models are used efficiently and effectively by many different companies active in different engineering areas. In some branches it is however not feasible to do it as there are rules and regulations prohibiting it. One obvious example is pharmaceutical products, which have to be designed, tested, produced, and documented according to strictly regulated procedures (Tobin & Walsh, 2008).

So, even though there are similarities concerning how engineering design takes place—it includes phases and activities such as prototyping, testing, formalising requirements, etc.—there are also great differences. It could well be argued that the differences are so great that we should not speak of *The Design Process*, but rather of a multitude of similar (but not identical) processes.

Summing up:

- Engineering is about creating or modifying products and processes according to somebody's (typically a manager's or a customer's) wishes.
- Engineering is a problem solving activity
- Engineering is a decision making activity
- The engineering design process …
    - can vary considerably between companies, branches, and technological domains
    - includes typical phases—prototyping, testing, formalising requirements—that are common to most (or all) technological domains
    - can be linear
    - can be iterative
    - can be organised with active customers and many partial deliveries
    - can be structured for maximum effectiveness and efficiency
    - can be structured according to branch-specific rules and regulations
- The quality of an engineering design process, method, or piece of knowledge is determined primarily by its effectiveness and its efficiency: Did it lead to a useful result? (*Was it effective?*) How much resources were spent while doing it? (*Was it efficient?*)

PRE-UNIVERSITY ENGINEERING EDUCATION

Pre-university engineering education covers a broad range of activities and learning objects: from young children building models from cardboard and clay to teenagers making calculations for how to balance an amplifier circuit; from craft-like skills to elementary engineering science; from designing for aesthetics to designing for advanced functions.

Where to Find the Engineering Education

Through scrutiny of curricula and policy documents from various countries, it is easy to find engineering elements, i.e. teaching and learning of skills related to engineering and the engineering design process. They seldom make up a subject on their own; *engineering* is not a common subject. Instead, the engineering elements form parts of other subjects, subject strands, or learning areas, e.g. *technology* (Sweden, New Zealand), *sloyd* [*crafts*] (Finland), *design and technology* (England, Scotland), *science and technology* (Northern Ireland), *science and technology/engineering* (Massachusetts), *science* (in *The Next Generation Science Standards*, 2013).

The reasons for this are often historical. The emphasis on engineering in school came up to speed in the 1990s, and as school systems are different the new contents were introduced in different ways. Naturally, the way the engineering contents are packaged affect how it is implemented. In Finland, where engineering is included in a crafts subject, the making aspects are strongly emphasized. In England, aesthetic design aspects are put forward. Connections to the natural sciences are held to be important in the American *Next Generation Science Standards* (2013).

Why Should Pupils Learn about Engineering?

A multitude of reasons for including engineering in the curriculum exists:

Modern citizenship. ITEEA's *Standards for technological literacy* state that technological design 'provides tools essential for living in a technological environment' (p. 90). The Swedish technology syllabus stresses the necessity for learning about how technology affects society and its development (Skolverket, 2011, p. 254). The New Zealand curriculum (2007) emphasizes pupils' ability to 'participate in society as informed citizens' (p. 32). The English curriculum has a slightly different take on the same theme, saying that 'High-quality design and technology education makes an essential contribution to the creativity, culture, wealth and well-being of the nation' (Department for Education, 2013, para. *Purpose of study*).

Everyday skills. In the Finnish syllabus for technical sloyd it is stated that pupils should develop 'an understanding for technical phenomena in everyday life' (Utbildningsstyrelsen, 2004, p. 240, my translation). English pupils are provided with the opportunity to 'develop the creative, technical and practical expertise needed to perform everyday tasks confidently' (Department for Education, 2013, para. *Aims*) through the study of design and technology. The National Academy of Sciences (Quinn et al., 2012) claims that education in science, engineering, and technology helps pupils to 'to make informed everyday decisions, such as selecting among alternative medical treatments or determining how to invest public funds for water supply options' (p. 7).

Problem solving and other general skills. A strong belief in pupils' ability to use skills, such as problem solving, gained in engineering education in other areas is expressed in some of the curricula. In Massachusetts, skills 'such as the ability to work through difficult problems, to be creative in problem solving, and to think critically and analytically will serve students in any setting. When students work toward high expectations in these areas, they develop the foundation they need for success after graduation' (Massachusetts Department of Education, 2006, p. 16). Finnish pupils develop their self-confidence and their skills in problem solving and group work through their sloyd projects (Utbildningsstyrelsen, 2004, pp. 240, 242). The Scottish curriculum promises that 'The skills that learners acquire by successfully completing this Course [National 3 Design and Technology, level 3] will be valuable for learning, for life and for the world of work' (Scottish Qualification Authority, 2012, p. 2). They will also develop 'perseverance, independence and resilience; responsibility and reliability; and confidence and enterprise' (p. 2). In addition to all this, design and technology is also said to be the most suitable subject for the study of sustainability and consumption of finite resources (Morgan et al., 2013). There are obviously strong beliefs in (or strong hopes for) how engineering practice in school can improve learning, work, and life in general.

Future careers in engineering and technology. The National Academy of Sciences (Quinn et al., 2012, p. 10) states explicitly that one of the purposes for science and engineering education is to provide a firm ground for future studies in the field. In New Zealand, '[l]earning for senior students opens up pathways that can lead to technology-related careers. Students may access the workplace learning opportunities available in a range of industries or move on to further specialised tertiary study' (New Zealand Ministry of Education, 2007, p. 33). This is in stark contrast to the curricula of e.g. England and Sweden, where future studies or careers in engineering are not explicitly mentioned.

Engineering also provides opportunities for collaborations between schools and industries (Banks & Barlex, 2014). Pupils can work with real engineering problems, or those based on real engineering problems, which can provide inspiration for and knowledge of possible future careers.

Learning in other subjects. Engineering as part of a larger cluster of educational areas is an essential part of the STEM concept, where *science, technology, engineering,* and *mathematics* are taught and assessed together (Banks & Barlex, 2014). If everything works out as intended, the traditional subject-boundaries are resolved and all unite into one coherent whole. To use technical artefacts and technical problem solving to illustrate concepts of school science has a long tradition. Especially physics textbooks tend to contain loudspeakers, steam engines, and aeroplane wings, used to explain sound and electro-magnetism, heat and pressure, and turbulence, respectively. To do things the other way round—to let the creation of technical artefacts lead to the necessity of finding out about scientific concepts—is prescribed in some technology and engineering curricula and policy documents. It is strong in The National Academy of Sciences' (Quinn et al., 2012) framework, where a long chapter is dedicated to the integration of science and engineering and how different practices, concepts, and core ideas can cross-fertilize: 'from a teaching and learning point of view, it is the iterative cycle of design that offers the greatest potential for applying science knowledge in the classroom and engaging in engineering practices' (p. 201).

Using knowledge from the science subjects in engineering design for mutual benefits is also stressed by *The Next Generation Science Standards* (2013, p. 81), where examples of how scientific concepts like biodiversity, chemical reactions, and forces during collision, are used in educational engineering design projects for the benefit of all.

Even ITEA's *Standards for technological literacy* puts forward engineering and technology education as a vehicle for school subject integration. Examples include not just science, but also for example history. They suggest history studies where the lives of yesteryear's people is understood through the technologies they used (p. 6 f.).

The reasons for learning engineering in school varies slightly between countries, but the ones mentioned above are common in curricula and similar documents. There is obviously a widely held belief of the usefulness (or even necessity) of engineering education in school: it teaches pupils general skills, it makes them understand modern society, and it helps them to learn mathematics, science, and other subjects.

What Should Pupils Learn about Engineering?

At the core of the engineering education that is described in the various syllabi and policy documents are design processes. These go under a variety of names:

- *crafts process* (Sweden—Skolverket, 2011, p. 204)
- *design* (Northern Ireland—Council for the Curriculum, Examinations and Assessment, p. 1)
- *design process* (Scotland—Scottish Qualification Authority, 2012, p. 2; United States—International Technology Education Association, 2007, p. 4)
- *engineering design process* (United States—Massachusetts Department of Education, 2006, p. 10; National Academy of Sciences, 2012, p. 46; *Next Generation Science Standards*, 2013, p. 23)
- *iterative process of designing and making* (England—Department for education, 2013, para. *Subject content: Key stage 3*)
- *phases of technical development* (Sweden—Skolverket, 2011, p. 256)
- *sloyd process* (Finland—Utbildningsstyrelsen, 2004, p. 240)

There are of course slight differences between these processes. In Sweden, for example, there are two similar processes: one in the subject crafts and one in the subject technology. They share common concepts like development of ideas and the necessity for communication, but differ e.g. in the role of manual work. Differences concerning the role of science, which tools that are used, the role of ICT in the development process, etc. varies. There is however a common core—identification of a problem, need or wish; development of solution suggestions; evaluation of these; etc. Whether the product shall be actually built (or implemented in some other way if it is an ICT or a biotechnology project) depends on what the learning objectives for the specific project consists of.

In the studied documents, very few details about the engineering design process models and their phases are to be found. In the Swedish technology syllabus, they are listed as 'identification of needs, investigating, proposing solutions, designing and testing' (Skolverket, 2011, p. 256). Pupils in Massachusetts use the following process: 'identify problem, research problem, develop possible solutions, select solution, construct a prototype, test the solution, communicate the solution, redesign' (Massachusetts Department of Education, 2006, p. 84). This is then followed by multiple cycles where the old redesign problem becomes the new design problem. The International Technology Education Association (2007, p. 123 f.) describes the design process thus: identify the design problem, identify criteria and constraints, refine a design by using prototypes and modelling, evaluate the design solution, develop and produce a product or system, evaluate final solutions and communicate results. These are all described in general terms, and supposedly useful for all kinds of engineering design projects within most technical areas. They all resemble the generic engineering design process in Figure 1.

The rough overviews of the engineering design processes from syllabi and general documents on engineering education are then worked out in detail in textbooks and similar materials for schools. On this level, significant differences can enter the process. Johnsey (1995) scrutinized and compared 17 different English design process models and showed that there many similarities, but also significant differences. The main phases of identifying problems and suggesting solutions are everywhere, but they are organised differently with some linear models and some organised with loops—allowing or even encouraging repeated try-outs. Concerning the process skills, there are also differences. Some identified 'planning' as a process skill, while other did not. Some identified the introductory 'research' as a process skill, while other did not. And so on. Even though most process models contained phases that were easily identifiable in pupils' work, the different models suggest important differences in what pupils are supposed to do and what they are supposed to learn.

How Should Pupils Learn about Engineering?

The ability to follow and implement an engineering design process is a set of skills, which commonly (but not exclusively) are said to include planning, technical drawing, technical reporting, testing, making, and evaluation. Many skills are difficult (or even impossible) to learn from books or instruction but must be practiced. This view permeates the notices about how engineering education should be organised in schools; there is a strong emphasis on pupils' actual designing and making, rather than just reading about it (McCormick, 2007). Pupils partake in product development projects that to some degree resemble real engineering design projects, but use other materials (cardboard, Styrofoam, and ice cream sticks rather than metals and concrete) and solve design problems that are different, easier, and do not lead to any severe consequences if they fail.

In most of the studied curricula or syllabi, there are few or no instructions concerning the 'How?' question. This is most likely a deliberate choice made to respect the autonomy of teachers and also to make the text withstand the passing of time better. A text that just states which skills (testing, planning, drawing, …) that pupils are supposed to learn will most likely be useful even ten years from now, something that one which states the tools to be used cannot count on being. For example, in a Swedish technology curriculum for secondary school from the early 1970s (Skolöverstyrelsen, 1970) large parts of the subject contents—technical drawing, solid mechanics calculations, characteristics of steel and concrete, etc.—are still relevant, but the suggestions for illustrating technical problems and phenomena using flipcharts or flannelgraphs are hardly so. Therefore, specific tools and teaching methods are seldom mentioned in curricula, and when specific activities are discussed, they are listed as *suggestions* or *examples*. To find out how engineering should be taught in school, we must therefore turn to other sources, such as handbooks and textbooks.

Various kinds of model cars are the objectives of many a school engineering design project. ITEA (2007, p. 122) describes an example where the teacher Ms. C.'s pupils are to build a model car from a limited set of materials including a sheet of paper, four wheels, axles, and some adhesive tape. The car is to roll down a slope and stop in a winner's circle. To solve the problem, pupils will have to work in teams, systematically test, improve, and re-test their suggested design, and put their knowledge of force, motion, and aerodynamics to use. Another example is provided by Johnston (2005) whose pupils build model cars that are powered by mousetraps. Pupils are to make the car move as far as possible, with 9 m set as the minimum. During the design process, they will have to use their knowledge about friction, transmissions, leverage, and similar mechanical principles and gadgets. A third example is listed in the syllabus of Massachusetts (Massachusetts Department of Education, 2006, p. 89). The model car in this project carries a passenger in the form of an egg. The major challenge for the pupils is to design a safety belt and deformation zones so that the egg remains unharmed if the car crashes into something.

These car model examples show another common aspect of school engineering projects: competition. Ms. C.'s pupils' cars are timed as they roll down the inclined plane towards the goal-circle; Johnston's pupils strive not just to make their mousetrap cars move the minimum length but also to be better than the others'. National and international competitions on technological themes, intended for children and adolescents, are common. Sometimes they are incorporated into engineering education. Two international engineering competitions that are popular in Sweden are First Lego League (with more than 25,000 participating teams from 80 countries in 2015, each consisting of up to 10 children) and Future City (originally an American competition, but now with national and regional offshoots all over the world).[2] First Lego League is centred on a specific theme each year, and the teams have to solve problems and work out ideas connected to this theme. The best known activity within the project concerns the designing, programming, and building of a Lego robot that is to move around a track, manipulate objects, etc. Other parts consist of coming up with ways to solve global problems and present the solutions to a jury. The engineering design process is emphasized in the Lego sub-project, and technology for the betterment of the world permeates the whole project. In Future City, pupils are to design a city or suburb. The competition varies between countries, but tend to include physical modelling in the form of buildings made from cardboard and *papier-mâché*, as well as virtual models produced in the Minecraft framework. Here too an engineering design process is practiced, and the use of technology for the betterment of society is highlighted.

SCHOOL ENGINEERING IS NOT ENGINEERING

In Garratt's (1996) textbook *Design and Technology*, intended for use in England, a strong emphasis is placed on the engineering design process (called 'the design process'). The process is described as a predominantly linear problem solving activity, starting with an investigation of the situation, which is followed by design suggestions, testing, etc., and results in a product that solves the problem or a prototype of such a product. It is similar to how linear engineering design processes outside of school are commonly described (Figure 1).

The engineering design process is illustrated by a story about Pauline and Nick, two clever and well-behaved pupils in their teens (Garratt, 1996, pp. 6–17). Pauline and Nick know an old lady, Mrs Brown, who finds it difficult to ascend and descend the stairs in her house. To help Mrs Brown, Nick and Pauline decide to design her a stair lift. They start with interviewing Mrs Brown and taking measurements of her house. Then they suggest design solutions, evaluate them, make drawings, and finally construct a reduced scale model and write a report about their work. The design project has finished successfully. This is a quite advanced, but in many ways typical engineering design task from pre-university education.

Nick's and Pauline's work would however not have been typical were they real engineers. There are multiple reasons for this. Nick and Pauline have not solved Mrs Brown's problem. The small-scale prototype made from wood and a small electrical motor cannot move a human being but is better suited for a small doll. It is therefore not of any use for Mrs Brown, and there are no plans to build the real thing. Furthermore, there is something most peculiar about their work process. They have forgotten one very useful method, namely to use other people's work. If Nick and Pauline had googled 'stairlift' they would have found that several products fulfilling Mrs Brown's needs are available on the open market.[3] They are modular and easy to fit into existing buildings. They also have all kinds of national and international safety certificates, and are not even particularly expensive. To make a new design from scratch for a one-off stair lift without any special features is not rational from an engineering point of view. It will be more expensive, less safe, and the project will take longer time—both process and product will most likely be less effective and less efficient.

So, even though Nick's and Pauline's project must be seen as a failure or at least a sub-optimal solution as an engineering project, it is put forward as a model example in a commonly used textbook. How can that be? The reason is simple. What Nick and Pauline partake in is not *engineering*, but *school engineering*. The purpose of engineering work is to fulfil needs and solve problems. The purpose of school engineering work is that pupils should learn a set of skills that can be useful in various situations, such as when doing real engineering work. Nick and Pauline learnt how to write reports, make technical drawings, build models, and perform tests. Therefore, they were successful even though their project was very time-consuming and no real problem was solved. The nature of school engineering is inherently different from the nature of engineering, and must so be.

The quality or rationality of a school engineering project does not concern the effectiveness and efficiency of the development or use of a product, but rather the effectiveness and efficiency of pupils' learning. One may very well occur without the other; if Nick and Pauline had bought a stair lift off the shelf that would have been efficient and effective problem-solving, but very little learning would have taken place. Similar situations can occur on higher levels of the educational system. Edin Grimheden (2013) describes how the introduction of Scrum—an agile product development method—has increased his university level mechatronics students' opportunities to learn through increased interaction with clients and greater opportunities to improve preliminary designs. At the same time he emphasises that even though the method is great for learning it is not suitable (or even allowed) in all real product development contexts. Enhancing learning does not necessarily lead to increased quality of the product or process.

This fundamental difference in purpose also seeps into other aspects of school engineering. It is not about developing products, but about developing knowledge and attitudes according to what is stated in the syllabus. This has led to the following common characteristics of school engineering projects:

Develop a new solution, even though old ones exist. A common first step of an engineering project is trying to find similar or identical products which can provide solution suggestions or inspiration. Perhaps it is not even necessary to develop a new product, maybe it can be bought off the shelf.

It is not unknown that teachers use the same tasks for the pupils year after year. In those cases pupils can often find good solution suggestions by asking older friends or siblings. While this would be called rational and efficient in a real engineering design project, it is commonly referred to as cheating in school.

Peculiar requirements. To avoid that pupils can base their design solutions on existing ones and make sure that they get the right kind of challenge, requirements of kinds that are seldom found outside of the school world are often used: the driving force of the model car must come from a mousetrap even though more suitable power sources exist; the model bridge must be a suspension bridge even though another type would be cheaper and better. Etc.

You can succeed even though your product does not work. When solving real engineering problems, the ultimate sign of success is generally a happy customer that is willing to pay for your work. In school, that is not always necessary. If your drawings are nice and tidy, your idea is well developed, and your final report is in accord with the provided template, you may pass (or pass with distinction) even though the product does not function as it was meant to.

Inefficient groups are encouraged. In real engineering work, experts tend to work within their fields of expertise. In school engineering, team members are often encouraged to do things that they do not already know. Learning, not efficiency in product development, has the highest priority.

Limited in scope. Mechanical, electrical, and electromechanical projects dominate school engineering in most countries. Biotechnology and chemical technologies are not common. The image of engineering that is purveyed through school engineering seldom give a representative picture of the whole field of engineering.

School engineering projects are nice and kind. Several school engineering syllabi stress that pupils should become environmentally aware and active, responsible citizens. This is often reflected in the themes for school engineering projects. They are almost never about weapons, and seldom about combustion engines or other such evils, but kind and nice. The stair lift project of Nick and Pauline (Garratt, 1996) is typical in this sense. So is a project about designing a shower for a developing country described by Denayer et al. (2003) and the themes for the First Lego League competition: improving schooling and learning (*World Class Learning Unleashed*—2014), avoiding natural disasters (*Nature's Fury*—2013), improve and maintain the quality of life for the elderly (*Senior Solutions*—2012), etc.

School engineering is not engineering, and cannot be engineering as the purpose is different. It must however be related to engineering for pupils to be able to use the skills and knowledge gained from school engineering projects in real engineering projects, future studies, and their everyday lives. The design of effective and efficient engineering education is not trivial, and neither is pupils' transfer of school engineering knowledge to engineering knowledge.

COHERENCE AND ALIGNMENT (OR LACK THEREOF)

The nature of engineering education can be studied and evaluated on multiple levels. Is it the wording of curricula, how teachers interpret them, or what pupils actually learn that is most interesting? In this article, it is mainly about the formal, curricular level. This choice has been made because the curricular level is reasonable stable. While classroom practice may change when a new, free CAD program is released or when the price of 3D printers drops, the curriculum can stay the same (or almost the same) for a decade or more. Another reason is of course that the curricular level is easily available for study, which classroom practice is not. A study of classroom practice can consider a handful of teachers, while a curriculum study can cover countries or continents. At the same time, it must be admitted that it is slightly unsatisfactory to leave the actual teaching and learning out. This is especially disturbing as engineering is a skill-based area of study. Engineering is learnt by practicing school engineering, and pupils' knowledge in the area must be assessed by studying their work. Thereby, the delimiting line between the 'What?' and the 'How?' becomes blurred—teaching method and subject contents cannot easily be separated. This is also obvious from engineering and technology curricula, where methods and activities show up in the contents descriptions (albeit as 'suggestions' or 'examples').

For a subject to form a coherent whole, contents ('What?'), methods ('How?') and purpose ('Why?') must fit together. If the purpose of the subject is to turn the pupils into brilliant problem solvers, then problem solving related contents should be included, and suitable activities to increase the likelihood of learning how to solve problems should take place in the classroom. This is really common sense. Nevertheless it is not always the case and lack of alignment between these different aspects of a subject occurs on all levels of the educational system (Biggs & Tang, 2011; Jönsson, 2010). In Sweden, the School Inspectorate has shown that the activities that take place in many technology classrooms are badly aligned with the curriculum—they do not reflect the subject's purpose of prescribed contents as many projects are too simple, their purpose is unclear to pupils as well as teachers, and reflection on one's own work and its relation to society is lacking (Skolinspektionen, 2014). The 'What?' and the 'Why?' in the curriculum are reasonably well aligned, but the 'How?'—the implementation—fails. Therefore, it can be controversial to make statements about the nature of a subject or area of learning without studying how teachers and pupils really work with it.

Figure 2 shows the most important dependencies for engineering in school. The two-headed arrows within the subject itself illustrates the interdependencies between the central aspects; what is to be learnt affects how it should be taught, but what can realistically be taught (due to matters of security, economy, available time, etc.) also affect which contents that are listed in the curriculum, for example. These relations determine the inner coherence of the subject.

The subject or area of learning is referred to as school engineering (engineering design, technology, design, …) and should in some way represent the engineering of the world outside of the school walls. School engineering is based on engineering, but engineering is not in any palpable way affected by school engineering. Engineering affects what should be learnt in school engineering as school engineering skills should be useful in real engineering. It also affects how school engineering should be taught, as many engineering skills are best learnt by doing them. Furthermore, it affects why school engineering should be studied, as it has to be realistic; there

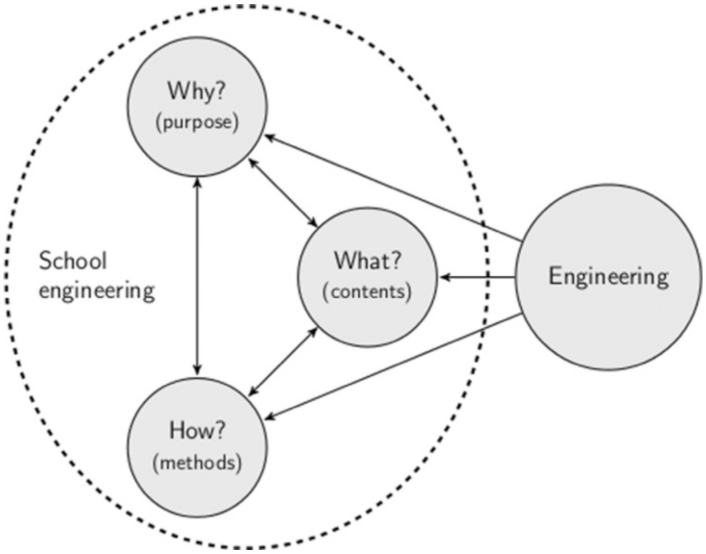

Figure 2. How different aspects of school engineering depend on each other and on real engineering

has to be a relevant mapping of what *should* be achieved in school engineering with what *can* be achieved in real engineering. From this follows that teachers must be knowledgeable about engineering. If the central aspects of school engineering are not strongly connected to the domain of engineering, its relevance for learning engineering can be questioned and it should really be called something else.

There are obvious similarities between the skills that pupils are supposed to learn through education in school engineering and some of the skills that engineers use. Teamwork, systematic problem solving, testing, and writing reports are all skills that are typical of engineering as well as of school engineering. The requirements are different, and many of the engineers' professional skills must be left out, but this is a normal part of the didactic transposition process—of making a teachable and assessable school subject out of something that is practiced outside of school (Chevallard, 1991). What is left out depends on the purpose of the particular subject; if the application of science has the highest priority, the use of standard procedures or methods based solely on experience should be discouraged and left out. If on the other hand the development of problem solving strategies are the ultimate purpose, the use of experience-based, non-scientific methods can be encouraged.

Just as it is easy to find similarities between engineering skills and school engineering skills, it is easy to see that school engineering classroom activities resemble engineering activities, at least on a surface level. The focus on making is in some countries (Finland, England) stronger in school engineering than in the typical engineering office outside of school. The tools are also somewhat different. The glue gun is probably more frequently used in Swedish technology classrooms than in any engineering design bureau in the whole world, and mathematical models are less frequent.

Whether school engineering is coherent, so that its purposes, methods, and contents can be united in a whole where the different aspects fit together and support each other, can of course not be answered once and for all. First, the subjects differ between countries, so any conclusions on the general level cannot be said to hold for an individual curriculum. Second, the methods—the 'How?' part—varies from school to school and from teacher to teacher.

THE TRANSFER PROBLEM

By comparing syllabi from different countries, it is obvious that great faith is put into pupils' abilities for transferring knowledge and skills from one domain to another. Pupils in Lake Norman High School (Mooresville, North Carolina) spend their engineering lessons designing catapults for ping pong balls and building towers from pipe cleaners.[4] They do this according to a prescribed engineering design process, similar to the first part of Figure 1. It is highly unlikely that any of them in their everyday lives will ever be approached by somebody asking: 'I don't know how to build a high enough tower from pipe cleaners, can you help me?' or 'I have a problem. I don't have a suitable piece of equipment for throwing a ping pong ball as far as possible. And it has to be constructed from ice cream sticks and rubber bands.' And if they are approached with such questions, they are probably being asked by another pupil in Lake Norman High School. For the skills learnt by designing and building pipe cleaner towers to be useful in the situations prescribed by the stated purposes of school engineering (everyday problems, future engineering studies, …), pupils have to repurpose their skills, which is not necessarily a trivial task. For this transfer to take place, many pupils will have to be guided by teachers making the similarities between school engineering and engineering explicit (*cf*. Banks & Plant, 2013).

The purpose of engineering (to solve problems and create products) and the purpose of school engineering (to make pupils learn) are inherently different. To be discussed here is if, how, and to what extent school engineering is related to the engineering outside of school. The above list of reasons for including school engineering in the curriculum contains such varied suggestions as increasing pupils' autonomy in the modern world, and helping them understand natural science. Is school engineering in its present incarnations really effective relative to these purposes? Do pupils develop the desired general skills and personality traits through practicing school engineering? At the time of writing (January, 2016), the sad answer is probably that nobody knows. I have been unable to find any conclusive evidence in the available engineering and technology education research. We have been teaching pupils about engineering in the hope of turning them into better, more responsible, entrepreneurial, and reflective human beings for over two decades, hoping, but not knowing for sure, that it actually works.

To determine the actual long-time effects of educational efforts is difficult. That said, it should be fairly easy to determine whether training in engineering skills is of help in everyday life and creates individuals with a stronger sense of responsibility. To do this, we could study engineers. They are trained in real engineering, which school engineering is based on. If knowledge about the engineering design process leads to people being entrepreneurial problem-solvers with a great deal of autonomy, engineers should possess these traits. Furthermore they should have excellent everyday practical skills, and the abilities necessary to select the right medical treatments and determine how to invest public funds for water supply options (*cf.* Quinn et al., 2012, p. 7). They should also have great understanding of the natural sciences and easily learn about history and complex aspects of society. Unfortunately, I have failed to find any evidence of engineers possessing these abilities and personality traits. If engineers, who are experts in engineering, do not possess them, what reasons are there to believe that pupils should develop them by learning engineering skills?

CONCLUDING DISCUSSION

Pre-university engineering education—or school engineering—is not, and cannot be, engineering. While engineering design projects strive primarily to produce great products, school engineering projects are focussed on pupils' learning rather than the product quality. Nevertheless there are similarities. Even though the tasks are different and the materials used are different, commonly school engineering design processes resemble idealised, linear engineering design processes. The expected and desired learning outcomes vary between countries, but tends to include general skills such as teamwork and systematic problem solving, as well as the application of knowledge from school science and an understanding of our technology-based society. It also often includes changing attitudes toward future studies in technology and science in a positive direction, as well as increasing autonomy and creativity. It clearly can be a varied and very challenging subject.

To what extent school engineering succeeds in what it is set out to achieve is an important question that has not yet received enough attention. Judging from international tests and attitude surveys concerning pupils' relationship with science and technology (Ardies, de Maeyer, & Gijbels, 2015; Sjøberg & Schreiner, 2010; Skolinspektionen, 2014) there have not been any dramatic increases in pupils' interest or abilities during the last decades when engineering has entered the curricula of many countries. Have the pupils become more creative? Have they developed a stronger sense for the environment? Are they better at teamwork outside of the engineering classroom? Can they apply a systematic problem solving approach to everyday problems? That is very difficult to say.

It is absolutely clear that school engineering is very demanding for the teacher. Changes in society, and changes in technology, makes continuous professional development absolutely necessary if the connection to real engineering shall be upheld. Teachers have to be knowledgeable about real engineering. Otherwise it is very difficult to guide the pupils' transfer of knowledge from the school engineering domain to the engineering domain. If you are to design a project about building mousetrap cars so that pupils develop useful general skills while participating is difficult in itself. To make the pupils understand how these skills can be of use when developing something else, such as a database system, is even more difficult. You cannot possibly do it without knowing what a database system is and what a database engineer does for a living.

The last word on *The Nature of Pre-University Engineering Education* has not yet been spoken. Whether school engineering actually can fulfil its many intended purposes is an empirical question which has not been thoroughly studied. Whether a general problem solving method that leads to effective and efficient solutions for a wide variety of problems exist, and can be learnt through school engineering, is also an empirical question that awaits an answer. And if it exists, why isn't it always used by teachers and curriculum designers when planning and executing engineering education?

NOTES

[1] See http://www.extremeprogramming.org and http://www.scrum.org respectively.

[2] See http://www.firstlegoleague.org and http://futurecity.nu respectively.

[3] There was no Google when the book was published in 1996, but they could have used AltaVista, visited the library, or asked an organisation for elderly or disabled people.

[4] http://iss.schoolwires.com/Page/55686

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