International Journal of Engineering Studies.
ISSN 0975-6469 Volume 5, Number 2 (2013), pp. 129-154

http://www.ripublication.com/ijes.htm

The Engineering Paradigm

Erik W. Aslaksen

Gumbooya Pty Ltd
3 Gumbooya Street, Allambie Heights, NSW 2100, Australia
erik@gumbooya.com

1. Introduction

In order to understand what something is, it is often beneficial to study its history, its development over time. Understanding how it came to be what it is today, the issues and problems that arose underway, how they were solved, and how this influenced the further development, all lead to an understanding that goes deeper than what is provided by the immediate appearance presented today. This method of historical analysis was applied to great effect by Thomas Kuhn and presented in his seminal work, The Structure of Scientific Revolutions (Kuhn 1996), and the title of the present paper reflects the inspiration provided by that work.

Kuhn showed that, for long periods of time, science works within a set of accepted truths and norms, which he called the scientific paradigm, and that it is the existence of this stable framework that, to a great extent, underpins the efficiency of scientific work. However, these periods of stability are interspersed by relatively abrupt changes to the paradigm, brought about by two factors: the number of experimental results that cannot be explained within the existing paradigm reaches a critical value, and a new theory is put forward that explains all or most of these results.

As we shall see, engineering has some similar characteristics. This has also been argued by E.W. Constant (Constant 1987), who called it a "culture of technology", expressed both in large-scale organisations and institutions and in the career committmemt of individual practitioners, that creates technological momentum, the propensity of technology to develop along previously defined trajectories unless and until deflected by some powerful external force or hobbled by some internal inconsistency. But adapting this picture of evolution to engineering requires us to take account of the significant differences between engineering and science. Basically, whereas science is about discovering the truth of our understanding of Nature, engineering is about using that understanding for beneficial purposes. And whereas the paradigm within a domain of science can change relatively rapidly, caused by a single revolutionary new theory, such as the heliocentric view of the solar system, Newton's laws, Darwin's theory of evolution, relativity, and quantum mechanics, changes within engineering are more gradual. In particular, is not that existing engineering knowledge and works are found to be incorrect and need to be discarded; it is that new knowledge and works are added and then, over time, replace the old for reasons of greater cost-effectiveness. Old engineering is like General Macarthur's old soldiers (Macarthur 1951).

Another difference was pointed out in (Grimson 2012). Science can be considered to be convergent in the sense that succeeding theories about an aspect of Nature converge on the truth about this aspect, "science proceeds relentlessly to gradually hew away the rough walls that imprison truth". But in engineering it is difficult to discern any such convergence over time, and even at a given point in time there may be several different solutions to a given problem. As an example, take the problem of handling (storing, transmitting, copying) information: from hieroglyphs on stone tablets to bits on individual atoms and from semaphores to teleportation, at any point in time a number of approaches were implemented and subjected to further development, and it is not possible to identify any final solution; the development is open-ended and divergent.

Finally, and at the core of the current investigation, there is another difference. If we define science as explaining and understanding Nature, then the concept of science is timeless, and we can ask such questions as "What is the first evidence we have of scientific activity?" and "What were the beliefs and norms guiding scientific activity at such and such a time?". But, as we shall see in the next section, the concept of engineering itself only emerged over a long period of time through a development that is, to a certain extent, still ongoing today, and so the concept of an engineering paradigm cannot be that of an environment in which engineering takes place, but rather the place and nature of engineering itself within a wider field of human activity.

That wider field of human activity may be described as the modification of elements of the natural surroundings in order to meet a need; what we shall call a *purposeful* modification. It started when humans developed the mental ability to recognise the possibility of such a modification and the physical dexterity to realise it, and the purpose included giving visual pleasure or increasing one's self esteem (painting, ornaments, sculptures), worshipping a deity (monuments, temples), providing shelter (dwellings), increasing mobility (roads, bridges, boats), providing food (traps, weapons, agriculture), preparing, serving, and storing food (bowls, pots, plates), and so on. This is roughly what the ancient Greeks identified as *techné*, and we shall investigate the development of that field of activity to the present day with the aim of identifying and defining an evolving subset of those activities as *engineering*. However, in order to study the evolution of engineering, this subset must be described as consisting of two parts: one that remains constant and allows us to identify it as engineering, we might call this the *essence of engineering*, and one that describes the evolution, which is the *engineering paradigm* mentioned above, and we do that below. But before doing that, it is appropriate to note how the word *techné* (which in Greek is spelt τεχνη, and would actually be *texnh* with Latin letters) has been used in the literature on engineering. According to the dictionary (LSJ 1940), the word means "art, skill, cunning of hand", and so, in the broadest sense, applied to any creative activity and the products that arose from it. When then engineering became a recognised profession and the subject of philosophical enquiries as to its content and purpose, much of the early work was in the German language, and the word *Technik* was adopted to refer to both the activity of and artefacts produced by engineering. (An important work in this regard is the book *Streit um die Technik*, (Dessauer 1956), to which we shall make reference further on in this paper.) As a result, the word *technology* took on this same meaning in much of the work in the English language on philosophical enquiries related to engineering. But within the engineering profession itself, technology means the knowledge and resource base engineers apply to create new works; the activity of creating the works is called engineering. No engineer would say that he is "practising technology" or "doing technology". But, depending on the context, engineering encompasses technology, as in "studying engineering". Understanding these two uses of "technology" is important, because while a philosopher may talk about the ethics of technology or the effects of technology on society, this makes little sense to engineers, as they see technology as completely value-neutral; it is only the application of technology that can have an effect and has ethical aspects.

2. Historical Analysis

2.1 Framework

The history of this wider field of human activity is documented in numerous books and papers, and covers a range of aspects, such as personal, technological, economical, social, philosophical, and religious. To analyse this extensive amount of information, we need to keep our objective in mind, and extract information which is relevant to that objective. That means limiting not only the subject matter of the information, but also the level of detail; it just needs to be adequate to support the conclusions we want to make in Sec. 3. That is the purpose of the analysis in this Section 2, and as our objective involves studying the evolution of a certain subset of the activities within this wider field, a first step is to define a suitable timeline, and the following will be used:

Period	Approximate duration
Ancient	Until 500 BC
Classical	500 BC to 400 AD
Medieval	400 to 1400
Renaissance	1400 to 1650
Enlightenment	1650 to 1750
Industrial Revolution	1750 to 1850
Production	1850 to 1980
Information	1980 and ongoing

This timeline has a decidedly "Western" look. That should not be taken to imply that activities we are interested in took place only in the West; on the contrary, up until about 1650 technology in China was equally advanced as that in Europe. The reason for adopting this timeline is, firstly, because the literature available in English on the history of technology and engineering generally adopts this, or a similar, timeline and, secondly, because the significant rate of change of engineering as a profession, and therefore the focus of our analysis, has taken place after 1650 and mainly in the West.

Then we need to define the characteristics of what we are looking for; that is, the essence of engineering and the engineering paradigm. The essence of engineering, i.e. that which identifies an activity as engineering, is that it

- *is creative*; there is an element of novelty or innovation in the product of the activity. Simply replicating something is not engineering, it is a production process that involves one or more trades.
- *is rational*; it employs a reasoning based in part on science and in part on heuristics (previous experience). together forming an identifiable knowledge base. *Art* also involves rational application of previous experience (although in some modern art this may be difficult to realise), but it relates to the process of producing the artwork, not to the artwork itself.
- *is useful*; in the sense that it results in products that, when used, provide services that meet needs expressed by parties external to the activity. Artworks provide their service (awakening a particular emotion) in themselves, without any active performance on their part.

The last criterion should not be interpreted as defining the value of engineering to be purely instrumental and have no intrinsic component; however, the existential value of engineering, as was discussed in (Floorman 1996), exists only in relation to the engineering community.

The aspects of engineering that change as engineering develops and that we shall take as defining the engineering paradigm, are

- the existence and extent of different activities within the wider field of activities;
- the relationships of engineering to the rest of these activities; and
- the nature and extent of the knowledge and resource bases that support engineering.

The following books provide the primary source material for our analysis: (White 1962), (Cuomo 2007), (Hart 1926), (Hill 1984), (Parsons 1968), (Rolt 1962), (Sprague de Camp 1963), (Turner and Goulden 1981), and (White 1962); a short synopsis is also given in (Aslaksen 2012). Some of the material is contained in more than one of these books, and similar information is often stated repeatedly in one book, but in different contexts, so it is impractical to identify each instance of information underpinning each individual outcome of the analysis, but where a particular item of information is quoted, the specific reference is given. And, of course, our purpose is not to comment on or develop further insight into history as such, but to use the existing material to discern the extent and nature of engineering activity.

The development of engineering and technology took place in various regions of the world; first in isolation due to a lack of communications, later one can trace the migration of a particular technology from one region to another. The regions of main interest up until about 1850, and for which most archeological and historical data is available, are the Far East (China), India (the Indus Valley), Egypt, the Middle East (the Fertile Crescent), and Europe (as exemplified by the Roman Empire). Developments in the Americas were generally of lesser extent during this time, and not of significant importance for our purpose, and areas like Australia and the Pacific islands did not develop much of relevance. However, from 1850 onward, the United States rapidly became a main driver of the development of engineering and technology.

2.2 The Ancient Period

Our knowledge of human activity in the time prior to written pictorial records, say, 4,000 BC, arises from archeological and anthropological work. Flintstones cleaved to give a sharp edge or point and used for various purposes, such as cutting and shaping wood, spear- and arrow-heads, and scraping hides, textiles made from plant fibres, ornaments made of various materials, and remnants of pottery all provide evidence of activities that display all three of our defining characteristics, although the claim to a knowledge base is tenuous and restricted to reproduction rather than to innovation. But the proportion of this type of activity compared to the daily struggle for survival was minute, and it was not until the development of agriculture and the establishment of settled communities, around 8,000 BC, that a degree of specialisation and allocation of labour specifically to what we can identify as engineering activities, according to the above definition, took place.

Initially, the work would have been carried out by individuals or small groups of individuals who we would characterise as craftsmen. They produced tools to shape materials, used these to produce various constructions, such as dwellings, rafts and boats, irrigation channels, and simple bridges, and they produced useful artefacts out of wood, clay, and metal for daily use. These innovations and inventions were possibly more the result of trial and error, or simply serendipity, than of any rational development, but in the course of this work they developed a knowledge base which was transmitted, for most of the period, verbally and by example from generation to generation, with any written or pictorial record of this knowledge base appearing only towards the end. Significant additions in this period included the smelting of metals (copper, bronze, and iron) and the manufacture of glass. However, as the communities were small and communication between them very limited, this knowledge base was geographically dispersed and its overall rate of growth very low.

As the communities grew in size, so did their ability to support a workforce not engaged in food production, and with that their ability to undertake large construction works. This introduced two new aspects to engineering. Firstly, for small artefacts, such as a new lock mechanism, a new type of hinge, a better plow, or a better wheelbarrow, the person who had the idea was also the person who produced the artefact, and in most cases the mental work of envisaging the new item and the physical work of producing it would have been so closely interwoven as to be indistinguishable. But with the increase in size, the object to be constructed had to be envisaged more or less in its entirety and described in some form prior to the start of construction, both to get approval from the relevant ruler and in order to be able to assemble and direct the workforce. That is, the activity we call *design* became discernable as a separate activity, but the designer and the builder would generally be the same person; there was no need for a formal interface between the two functions. And the design description, in whatever form it was, a drawing or a model, would have been used mainly by the designer/builder, our embryonic engineer, himself in order to ensure the consistency of his instructions to the workforce.

Secondly, such large projects introduced the aspect of *management*, both of the workforce (sometimes slaves) and of the materials supply (timber, ropes, suitable stone, clay for bricks, etc.). For the larger projects in the latter half of the ancient period, such as the pyramids in Egypt, the Palace of Minos on Crete, and the large irrigation works in China, the management (i.e. the planning, resourcing, and controlling) of the construction process would have been the main task, and it is fair to say that throughout the whole of this period the development of engineering was to a large extent the development of the construction process, the ability to undertake major projects. This is also evidenced by the fact that the names associated with most of these large building works are the names of the professional administrators or government officials that planned the project, not the engineers that designed the works (Turner and Goulden 1981, p. xvi).

2.3 The Classical Period

In this period the development of engineering advanced more rapidly than in the ancient period, both because of the accumulating knowledge base and because of improved communications (travel, trade) that disseminated this knowledge beyond its location of initial discovery and development, and we can distinguish two components of this development. One was driven by the rise of science (in particular mechanics), both theoretical and experimental, resulting in the invention of a large number of tools, devices, and mechanisms; the beginning of what we might characterise as mechanical engineering. Examples would be various types of water wheels (overflow, underflow, vertical), various types of water elevating mechanisms (pumps, Archimedes' screw, bucket chains), clocks, improved gear wheels, surveying instruments, tools for agriculture, and also process installations, such as mills, kilns, and furnaces. In some cases these devices appear to have been developed more as a demonstration of the physical principle and as a demonstration of a possibility, rather than as a product for sale, and the reasons would have been the cost of the material (e.g. steel was produced by hand forging) and the lack of a production technology that would have made the production cost-effective. In one respect, however, the advancement of engineering in those days displayed a similarity to what it is today; it was driven in part by the desire for military superiority. The development by the Greeks of the catapult, in various forms, led to what has been called "the Hellenistic revolution" in warfare, and led to lamentations about the demotion of hand-to-hand combat (Cuomo 2007, p. 41) (probably much the same sentiment as the Taliban have towards unmanned drones).

The other component was the emergence of a more sophisticated approach to the design and building of structures and civil works, as well as to the management of this work, driven by the demand of the large empires (Chinese and Roman) for roads, canals, viaducts, sewers, walls, and fortifications. This resulted in a construction industry that was organised for efficiency and that delivered consistent results. It was no longer acceptable for the individual builder to rely solely on his own knowledge and experience; the body of knowledge started to contain generally accepted processes and designs. An outstanding example of this is the design and construction process for major Roman roads.

At the end of this period, engineering activities had taken on a more distinct character and had become somewhat structured. While it was still true that the designer and the builder was often the same person, the design was recognisable as a separate activity with an interface, in the form of a drawing or a process description, to the building of the object. And the design activity itself had become diversified, whether it was the design of the object or of the associated production process; significant disciplines included mining and the smelting of ore and metals, civil/structural works and the production of cement and concrete, the design of buildings (i.e. architecture), and shipbuilding. In all of these there was an increased influence and content of science, but there was also a belief in Nature's active involvement, sometimes coupled with religion, such as the blessing of a new enterprise and calling on divine support, and there was a strong artistic influence. Design was a holistic expression of man's creative abilities, not just of the rational aspect. This was most visible in the separation of the design of buildings from the design of e.g. a road or a drainage channel: form and function were balanced in the former, whereas the latter was focused on the functional. Architectural styles (or patterns) developed, such as the Roman villa, the Vastu Shastra mandala in India, and the distinct Chinese architecture. Further evidence of the importance of design is that we now find the names of designers, such as Agrippa and Appollodorus, or Shih Lu in China, associated with their works.

An important aspect of the emergence of an engineering profession was the increased level of literacy and the availability of writing material; bamboo and then paper in China, and papyrus and then parchment in the West. The knowledge base became documented, and the ability to use and contribute to this knowledge base became a hallmark of the engineer as opposed, say, to the craftsman. Perhaps the best known example of such documentation is a set of ten books on architecture, *De Architectura*, by Marcus Vitruvius (Vitruvius 20 BC), a Roman engineer and architect, who served for many years as a military engineer, including in Caesar's Gallic campaigns. Of particular interest is Chapter 1 of Book 1, entitled "The Education of the Architect", which emphasizes the broad scope of the education, which should include arts, science, practical knowledge of materials and construction methods, and more, but also recognises that the depth of some of these more auxiliary areas needs to be limited; a first recognition of the enduring problem of balancing the engineering curriculum!

Another well known example are the various books and treatises by Archimedes, of which only some have survived. Archimedes was principally a mathematician and physicist, but also an engineer who invented novel mechanisms, such as the spiral water pump. It is interesting to contrast him with Vitruvius, because the contrast between the Greek scientist and engineering designer and the very practical Roman engineer illustrates the different attitudes of the Greeks and the Romans to technology. Besides the noted military applications, the Greeks were mainly interested in technology as a demonstration of the laws of Nature and in the philosophical questions arising from the relationship of technology to society, whereas the Romans were not very interested in theory and took a pragmatic approach to engineering.

Finally, it is worth noting the importance of government institutions in both China and the Roman Empire. In China the majority of engineering was concentrated in several organisations under the direction of the imperial government, including the Imperial Workshops, the Arsenals, the Office of Works, and the General Water Conservancy, and while the high degree of organisation was initially beneficial, it turned into a rigid and bureaucratised system that a thousand years later made technological innovation and progress almost impossible. In the Roman Empire much of the engineering was organised within or in association with the military and developed mainly to meet the needs of the expanding colonisation for housing, fortifications, water supply, sanitation, and communications. These large concentrations of people engaged in engineering activities would have contributed significantly to the rate of development of the body of knowledge and to the recognition of a certain coherence and common basis for these activities and thereby sowing the seeds for engineering as a profession.

2.4 The Medieval Period

The thousand years from 400 to 1400 would turn out to be effectively wasted years as far as the progress of engineering in Europe was concerned, although existing methods and devices, such as various types of water wheels, continued to be employed and developed to some extent. There were a number of factors that conspired to make this so. First of all, the collapse of the Roman Empire and its dismemberment and destruction through the incursion of both Mongols and Germanic tribes meant the end of the state-sponsored and organised Roman engineering. For example, public sanitation in Paris at the end of the period was inferior to that of Rome at the start of the period. Then the rise of the Christian church, with its focus on life after this and its opposition to science and to education and intellectual enquiry outside its control, led to the loss of much of the knowledge base, although architecture flourished in the form of numerous chuches, such as the Hagia Sophia, Rheims, Amiens, Notre Dame, and Canterbury Cathedrals. And the small states and fiefdoms that now made up the western world did not, individually, have the economic power to pursue major engineering projects, and anyway spent much of their energy fighting each other or the Muslims, although again architects benefitted by building numerous castles.

China maintained its national integrity, and engineering continued to advance, but at an ever diminishing pace, due to the rigid social system. Many major hydraulic works (canals),roads, and bridges were built in this period, and a number to engineering inventions were made. But due to the turbulence on its western borders there was little or no communication with the West, so that such major Chinese engineering developments as paper and cast iron took a thousand years to reach the

West. The only exception to this dismal state of affairs (from an engineering point of view) was a result of the rise of Islam and the establishment of the Arab Caliphate (or Arab Empire). Islam was not adverse to science, and Arab rulers encouraged scientific research, with the result that significant progress was made in mathematics, astronomy, physics, chemistry, and medicine. As part of this effort Arab scholars also translated many of the Greek texts, and it is thanks to this that this knowledge was preserved through the medieval period. But aside from applications of this scientific effort into medical practice and to agriculture, including the construction of pumps for irrigation and mills for grinding grain, the Arabs were not particularly interested in using the advances in science to progress engineering; their mode of transport remained riding on horse or camel, so there was no great need for major roads and bridges, and the heritage of the nomadic lifestyle left its imprint on their society.

However, towards the end of this period, there was a change in attitude towards Nature; it was no longer seen as only something one had to accept, but also as something one could exploit by active intervention. Mining and metal processing and the use of water and wind power were the main areas of activity, and along with this activity came the increased confidence in the ability to understand Nature; the properties of materials and the actions of the forces, and on the basis of this understanding the ability to determine how best to exploit them. An expression of this new confidence is the statement by Roger Bacon in *De secretis operibus*, around 1260: "Machines may be made by which the largest ships, with only one man steering them, will be moved faster than if they were filled with rowers; wagons may be built which will move with incredible speed and without the aid of beasts; flying machines can be constructed in which a man may beat the air with wings like a bird; machines will make it possible to go to the bottom of seas and rivers." The only thing he missed was space travel.

2.5 The Renaissance

There are many differing and controversial views of this period in history; what caused it, why it originated in Florence, how much of a discontinuity it was, and how influential it was in shaping the different areas of activity, such as science, art, government, commerce, education, etc. However, as far as engineering is concerned, its significance is undisputable, because from this time until the 20th century, the development of engineering is located almost exclusively in the western world, i.e. Europe, England, and America (mostly the United States). And it is not the actual advances in engineering, although they were significant, that are of greatest interest; it is the tremendous outburst of creative and intellectual effort. It was as if a pent-up reservoir of creative energy suddenly burst forth; the classical knowledge and focus on philosophical enquiry were rediscovered (partly through Arabic translations), and science, art, architecture, and engineering, combined and separately, produced works of unprecedented beauty, functionality, and complexity. Well known people and their works that fall in this period include Leonardo da Vinci (Mona Lisa, Last Supper, and numerous note-books on engineering, art, medicine, and science, although mostly published only much later and therefore, unfortunaltely, of relatively little practical importance), Michelangelo (David, Sistine Chapel, St. Peter’s Basilica), Vesalius (On the Workings of the Human Body), Luther (Reformation), Machiavelli (The Prince, The Art of War), Pico della Mirandola (Oration on the Dignity of Man), Brunelleschi (Dome of the Florence Cathedral), Brahe, Copernicus, Galilei, Kepler (all produced major works in astronomy), Gutenberg (printing with movable type) and Francis Bacon (New Method).

In engineering, some major developments in this period included the following:

- Improvements in manufacturing, both in the sophistication of the design of the manufactured items, and in the accuracy of the manufacturing process itself. The latter was driven, to a large extent, by the demands of clock-making; clocks became the model for accuracy and improvements in technology, going from water clocks to mechanical clocks, and within these from weights to springs as the energy source, and with pendulums as the time-keeping element.
- The first examples of standardisation, such as in gears (for clocks) and screws.
- The emergence of production machines, such as an early nail-making mill in Nüremberg (Turner and Goulden 1981, p. 159).
- New designs based on the improved understanding of physics, such as the suction pump.
- Mining developed into an industrial process, with proper design of both the excavations and of the equipment used for ore transport and for dewatering, and with the introduction of blasting.
- Textbooks became more readily available, such as Agricola's *De re metallica* (15xx) on mining and metallurgy, and two books on mechanical engineering, *Theatrum Instrumentorum et Machinerum* (1578) and *Le diverse et artifiore machine* (15xx), by Agostino Ramelli.
- *De re metallica* (1556), and *Le diverse et artifiore machine* (1588).

In this period, engineering and architecture became reasonably clearly distinguishable, although some people, like Leonardo da Vinci had the title of *senior military architect and general engineer* when he was employed by Cesare Borgia. Architects developed a distinct style by reviving and extending elements of Greek and Roman architecture, and designed buildings of various sorts, such as cathedrals and churches, chateaux, fortifications, town halls, and other government buildings, whereas structural engineers designed bridges and industrial structures, such as furnaces, kilns, hoisting towers, piers, and the like. The evolving difference between architects and engineers makes it possible to perceive the appearance of a few characteristics of engineering that would become more sharply defined in subsequent periods, as we shall see. The first is that, while architecture was closer to art and therefore architectural works were much more readily identified with individual architects, engineering works were often more in the nature of creative applications of a body of knowledge and more closely circumscribed by the required functionality, so that the creative aspect was not readily visible to the general public. Secondly, the creative and artistic aspect of an architectural work (the vision) would generally be the work of a single person, whereas the creation of engineering works were often the result of teamwork, with each member contributing his special knowledge and skill. Thirdly, this period saw the beginning of private industry. While outside of the major government enterprises, such as works for the casting of cannon or shipbuilding, most private activity was still in the form of small craft shops run by a few family members, some of these now grew to a size where they could afford some serious investment in facilities and equipment and, most importantly, in the development of new processes and products. Significant industries included the spinning, dyeing, and weaving of wool and silk, mining, clay products (from bricks to porcelain), metal casting (with cast iron rapidly becoming more common), brewing, and printing. As a result, there was a developing market for engineered products, such as pipes, tanks, fittings, valves, pumps, shafts, bearings, different types of wheels, and tools of all sorts, and with it a demand for people who could design these products.

The fourth, and for the emerging profession maybe the most important characteristic was the change in its relationship to its environment, brought about by the emerging industrialisation of that environment. Up until the Renaissance, the only engineers that could be identified as such were the civil (including structural) engineers. They were employed by government bodies to design and manage major public works. The people undertaking other engineering work (mechanical, mining, and metalurgical) were generally identified as tradespeople, such as clockmakers, millwrights, coopers, smiths, etc, and worked mostly within the confines of their guilds. But with the emergence of engineered products and the importance of product design, the engineer (as the creator of these products) started to become disassociated from the guild structure. A product, such as a pump or a crane, would require skills in casting, forging, metalworking, and woodworking, and pumps were required in different industries, e.g. mining, brewing, dyeing, etc. So, while the guilds continued to keep their grip, to varying degrees, on the workers (brewers, weavers, bakers, stonemasons, etc) for several centuries, the people engaged in engineering activities started to become identified by the nature of those activities (mechanical, metalurgical, etc) rather than by the industry in which they employed them, even though they might originally have been trained in a trade, e.g. as a millwright, as there was not yet any formal engineering education available.

2.6 The Enlightenment

For engineering, the most significant development in this period was the rise and influence of science. The rediscovery of classical texts on topics such as mechanics, mathematics, and geometry, as well as the translation of texts from Arabic on these and other subjects, including medicine and chemistry, and then the dissemination of these works through printing in the Renaissance period, had provided a foundation from which scientific enquiry and discovery could take off. The Royal Society of London and the Académie des Sciences in Paris were both established at the beginning of this period, and the belief in reason and investigation, as opposed to mysticism and religion, led to numerous advances in philosophy and science and, above all, to an increased confidence in human intellectual ability and the value of the individual. Knowledge based on science started to replace the lore of the tradesman, and calculations started to supplement the experience-based judgement, initiating the separation between engineering and the trades. The scientific activity brought with it a demand for better instruments and measuring devices, which in turn supported the production of more complex industrial products. Again, clocks were the yardstick for engineering precision, but printing with moveable type also placed more stringent demands on the precision of the associated equipment.

Coupled with this increase in knowledge, understanding, and capability came an increase in the size and sophistication of industrial enterprises, with plants supplying such products as alum, lime, bricks, glass and soap, and a Swedish engineer and industgrialist, Polhem, constructed a rolling mill for producing wrought iron that supplied a significant part of the European market, and this same enterprise also produced standardised gears for clocks (Turner and Goulden 1981, p. 244). This development brought with it the need for capital investment, thereby sowing the seeds for a separation between the owner/business man and the tradesman/engineer.

2.7 The Industrial Revolution

Just as the political, social, and economical conditions came together in Florence around 1400 to provide the tinder for igniting the Renaissance, so a number of conditions in England around 1750 came together to provide the basis for the Industrial Revolution and, with it, a tremendous boost for engineering. Technology (i.e. the engineering knowledge and resource bases) had reached a point where it was effectively looking for applications. England's role as a supplier of manufactured goods to its colonies was creating a demand for greater output and providing the capital for investment in industry. England had the best patent system in the world, and government bureaucracy and social impediments to new enterprises were both significantly less than on the Continent. Finally, an abundance of coal and iron ore in close proximity (as well as the need to reduce the consumption of charcoal) provided the resources for the two hallmarks of the period: steel making and steam power.

As with the Renaissance, the Industrial Revolution soon spread beyond its place of origin (although the English were, of course, more keen to export the products than the technology), to the Continent and, in particular, to the newly independent United States of America.

As a profession, engineering started to organise itself, with the Society of Civil Engineers being formed in London in 1771. Here "civil" meant as opposed to military; the founding members included two surveyors, an architect, a lawyer, and four millwrights. The main purpose of this Society seems to have been as an interface between industry and government; for the development of technology the concentrations of engineers in the various significant enterprises, such as Boulton and Watt's Soho workshops were more important. Due in part to its development into a select industrial-political "dining club", the Society was replaced by the Institution of Civil Engineering in 1818, and by the end of the period it had about 800 members, many of which were associated with the by then very important railway industry.

Other countries followed suit, and by the end of the period we find the Verein Deutscher Ingenieure (VDI) in Germany, the American Society of Civil Engineers and Architects in the US, and the Civil Engineers Society in France. This period also saw the appearance of formal, university-based education for engineers, with the founding of L'ecole Polytechnique in Paris in 1794 being the first (although it was preceded by L'ecole Des Ponts Et Chaussées in 1747) and, in many ways, the model for those that followed. By the end of the period most “industrialised” countries had higher education in engineering in one form or another; a glaring exception was England (but not Ireland and Scotland), the cradle of so much of engineering, where a practice-based training was preferred until the 1870s.

2.8 The Production Period

The name of this period (which has no significance outside of this paper), from 1850 to 1980, is meant to highlight what was, for the engineering profession, one of the three most significant characteristic of this period – the advent of mass production of technical artefacts. This impacted the relationship between engineering and (the consumer) society, and also changed the role of the engineer in industry. Instead of being one of the main players, if not the main player, in creating new products, the engineer became just one of many cogs in the industrial machine, together with sales, marketing, legal, human resources, management, and others.

The second significant characteristic was (and still is) the increasingly close connection between engineering and science and mathematics, which has influenced the engineering profession in a number of ways. Firstly, it led to engineering sometimes being characterised as “applied science”, thereby devaluing and diverting attention from the main characteristic of engineering – as a creative activity. Secondly, with the advances of science into new areas, such as electromagnetic radiation, electron emission, ionisation, solid state physics, organic chemistry, and biology, engineering was forced to undergo an increasing specialisation in order to absorb and process these advances into its own foundations. Thirdly, the advances in mathematics and computational techniques led to the increased use of mathematical formalism and abstraction in the formulation of engineering procedures. Fourthly, and as a result of the forgoing, what might be characterised as the scientific part of the knowledge base of engineering expanded at a rate that left the profession in a quandry regarding how to handle it and at the same time accommodate the other parts of the knowledge base, those relating to practical experience and to the interaction with society.

The third major development in this period which had a profound influence on the profession was standardisation, both in the engineering itself, i.e. the activity, and in its resource base, i.e. in the elements and materials from which the products are created. Much of the design activity in engineering became a process of selecting a combination of existing elements; it would be inconceivable to start designing bolts, nuts, resistors, capacitors, semiconductors, steel sections, etc. when they can be selected from catalogues. As a result, the profession became further subdivided, not only into the various disciplines, such as civil, structural, mechanical, electrical, chemical, and so on, but into layers or strata identified by their locations in the process of converting raw materials, like silicon or steel, into end products, such as a mobile telephone or a car. Clearly, the skills needed at each level differ considerably.

As a part of the industrial production process and subject to the same pressures of cost-effectiveness, the process of engineering itself also became highly standardised. Thousands of standards, from company standards to international ones, defined how engineering had to be performed; the steps to follow, the documents and reviews to be completed at each step, the formats of the documents, and so on. Related to this standardisation of the engineering process was the greatly increased influence of the legal profession. It is not clear which one is driving which, it is a vicious circle, but the result is that a great deal of effort goes into insuring that one has complied with every condition in the standards (as specified in the contract) and any legislative requirements rather than into any creative activity.

Two developments in this period are of particular importance to our analysis. The first was that, with the advance of technology, the process of converting a design into a physical object changed in nature from a traditional craft or trade into a number of routine, but more complex activities that had to be formally taught in the course of a four-year apprenticeship or some other form of training. Often this training was tied to a particular machine, such as a complex numerically-controlled machine tool, or to a particular process, e.g. in the chemical industry. The result was that the engineer, who might in previous periods have been initially trained in a trade, such as a millwright, became somewhat separated from the end product. Design and production became separated by a formal interface, in the form of documentation of various forms (drawings, specifications, data files, etc.).

The second, which was a consequence of the standardisation, was the appearance of two additional professions - technician and drafter - taking some of the routine work off the engineer. The technician was present in the manufacturing and processing industries; the drafter (further subdivided into tracer and design drafter) was found in all industries, but particularly in the consulting engineering companies. The technician was most often a tradesperson with additional training and/or formal education, with the professional classification and requirements differing from country to country.

2.9 The Information Period

In this period, in which we are currently located, the engineering profession is experiencing the impact of further major development; comparable in its impact to the rise of science in the previous period, but of a very different nature – the advent of what only a few decades ago would have been unimaginably cost-effective computing power and the associated rise of a whole new branch of engineering, software engineering, and its product, software, with software engineering now said to account for more than half of all engineering effort. Computers and their software are being embedded in more and more products, from inexpensive toys to cars (40 % of the cost of a top-of-the range BMW is in its electronic systems), and, as an example, an industry like mining has been transformed from a rough and ready, rip-and-blast activity into a highly sophisticated, computer-controlled operation. And the impact on everyday communications and data processing can be seen everywhere, with the proliferation of smartphones and tablets.

For engineers (but for other professions as well), whether software or hardware engineers, the most significant aspect of this change is that the computer (and its software applications) has become not only the main communications interface, but also a production tool; taking over an increasing proportion of the routine engineering work, such as calculations, optimisations, and generating production documentation.

This is allowing engineers to devote more of their time to the creative aspect of engineering and increase their productivity, but not to the extent one might expect. The main reason for this is that while the software applications become increasingly more powerful and sophisticated, the knowledge and the formality required to use them also increases, so that engineers spend a lot of their time coming to grips with how to use the packages. Mastering a powerful application can be comparable to learning a new language; to that is added the effort to keep up with the frequent version changes.

3 Paradigm Shifts

3.1 A Particular View of the History of the Engineering Profession

In sec. 2.1 we defined engineering as an activity that meets three criteria, which together constitute what we called the essence of engineering, and then we defined the engineering paradigm as consisting of three aspects of this activity. When we now investigate how that paradigm has changed over time, on the basis of the historical analysis in Sec.2, then that is obviously a very particular, or restricted, view of the history of engineering. Many other important and interesting aspects of engineering can be studied in a historical context, such as the influence of engineering on GDP, on social conditions, and on health; also the role of engineering in warfare, how it influences security and economic stability, and so on. To understand why we have chosen the three particular aspects to define the engineering paradigm, we refer again to Kuhn's work on the scientific paradigm. That paradigm is the intellectual environment in which science operates, made up of a set of accepted theories, assumptions, and methodologies under which ongoing work is carried out. This paradigm is generated by the scientific community itself, and the ability to generate and maintain such a paradigm is an important characteristic of the scientific community. But an equally important characteristic is the ability to change the paradigm when certain conditions arise. The first ability ensures the viability of the profession as a cost-effective contributor to society at any point in time, the second ability ensures the long-term relevance.

The engineering paradigm, as we have defined it, is the environment in which engineering (again, as we have defined it) takes place and, as we shall demonstrate presently, it has also changed over time, albeit much more gradually than has been the case with science. But, as with the scientific paradigm, the changes are driven by engineering itself. By being performed, i.e. applying the existing technology, engineering generates new technology, and these additions to the technology require changes to the paradigm in order for engineering to be able to continue to apply the technology cost-effectively. However, as we mentioned earlier, because science is about ideas, the scientific paradigm is contained within the scientific community itself, whereas engineering, in order to be useful, needs to operate in an external, physical environment, essentially a part of industry, so that the engineering paradigm is of a different nature to that of science. And, in particular, whereas in science the reason for a change, i.e. the new theory, is different each time (e.g. heliocentricity, gravity, evolution, relativity, quantum mechanics, etc), we shall suggest that in engineering the reason for a change is always the same.

Now, in the case of science, it is impossible to foresee what the next paradigm change will be and when it will take place. But, because of the above difference in nature, the change in the engineering paradigm has a certain predictability, and examining that will form the conclusion of this paper.

3.2 The Historic Changes to the Engineering Paradigm

In the *ancient period* it is unclear (or unknown) how the engineering activity was performed. When an inscription says “so and so built this”, this person was generally a high-ranking government employee and may have been mainly an administrator or project manager and had other persons engaged to do the engineering work. In any case, it is reasonable to assume that for most of the period and in most places engineer, architect, and craftsman were indistinguishable as professions and that the work that could be identified as engineering, in the form of an embryonic design activity, was performed as an integral part of the building work, with no formal interface to the rest of the work.

There was also no reason for a professional distinction to develop. There would, of course, have been significant differences in importance and reputation, both within a project and within society, due to such factors as personal ability, family wealth and connections, training opportunities, and so on, but the technology (knowledge and resource bases) was so limited that there was no need for any specialisation.

However, one distinction within the wider field of purposeful activity was present already in this period and was, indeed, already present well before this period, and that is the distinction between engineering and art. The basic distinction is that the products of art fulfil their purpose by just *being*, whereas the products of engineering fulfil their purpose by *being used*. Of course, many objects are the product of both engineering and art, such as a ceramic bowl decorated with various scenes or patterns

In the *classical period* we can perceive the beginning of professional distinctions. Many of the works are what we would call architecture in that, besides the function of the works, the form and structure was to convey a sense of harmony, beauty, and awe of a deity or a ruler. In other words, the works were partly art works, and the persons creating them would have to have not only a good knowledge of the building trade, but also artistic talent and a broad knowledge of the beliefs, symbols, and customs of their society, and these are the requirements described by Vitruvius (*op.cit.*). But there are also many examples of works we would call engineering, and within these also a separation into civil/structural works, such as canals, drainage works, water supply tunnels and viaducts, and roads, and mechanical devices, such as pumps, clocks, waterwheels, windmills, grain mills, and catapults. To the extent that we know the people involved and their roles, there was now a fair, if not complete, distinction between architects and engineers, and the reason for this (as well as for the distinctions within engineering) was that the extent of the technology made it uneconomical for a person to acquire it all, given the lack of formal engineering education opportunities and the relatively slow rate of knowledge acquisition provided by “on the job” training. Of course, there were exceptions, and there continued to be exceptions until modern times, but specialisation would be an unavoidable consequence of the accelerating pace of growth of technology.

A related distinction that started to make its appearance, although to a very limited extent, was the distinction between the architect/engineer and the craftsman. There had, of course, always been the distinction between the designer/builder/manager and the labour required to produce the result, be it a canal, a pyramid, a viaduct, or a temple, but now the relative complexity of the works and the precision required would have resulted in certain formalisation of the various skills, such as mason or smith, and a distinction between the people possessing them and simple labourers. This would be the beginning of the guild system.

An important, but apparently very poorly documented development in this period is that of *industries*. Considering e.g. the amounts of bricks and concrete used by the Roman engineers, and their emphasis on efficiency, there must have been significant production facilities for these products (including their components). These, as well as major mining sites, must have had some of the organisational and process aspects and problems found in modern industry, and there must have been people that gained experience and skills in handling them. They would not have been readily identifiable as civil, structural, or mechanical engineers, but they performed engineering work and contributed to the development of technology, and this emerging duality of designing a product and designing the process to produce the product would develop into perhaps the most significant characteristic of engineering.

In the *medieval period* the main change to the environment in which engineering work took place was the increased organisation of crafts into *guilds*. As a result, a distinction between engineering and craft developed in that an engineering project would normally involve more than one craft, so that, even if an engineer was trained in a particular craft, his work would elevate him above the craftsman and free him from the restrictions of the guild.

The reawakening of the interest in and acceptance of science in the *Renaissance period*, as well as the rise of printing, started a transformation of the knowledge part of technology from being based exclusively on experience to having a theoretical component. The engineer now started to know not only what worked, but also why it worked. This was an essential change, as it allowed the development of new technology to be based on a reasonable prediction of what would work, rather than on a pure trial-and-error approach. It not only increased the creative productivity of the engineer significantly, but this relationship to science served to distinguish the engineer even more from the craftsman. And instead of the secretive knowledge base of a guild, engineering developed a free exchange of knowledge, out of which rose the patent system. Instead of restricting the knowledge, the patent system placed some restrictions on the commercial use of the knowledge.

Engineering became a more distinct activity, both with regard to architecture and to the crafts and trades. It also became more and more associated with industry and manufacturing, rather than being mainly concerned with construction, so that the previously mentioned duality of product and process became increasingly obvious and important.

For engineering, the *Enlightenment period* strengthened the ties to science and saw the further development of the scientific content of the engineering knowledge base. In particular, the design and production of increasingly complex machinery for the manufacturing industry led mechanical engineering to be more clearly identified as a separate discipline within engineering; a development that would be completed in the next period.

The *Industrial Revolution period* resulted in a significant change in the engineering paradigm. By the end of the period engineering was firmly established as a profession, with the civil and mechanical disciplines defined and the foundations for the further development of the internal structure in place. Formal engineering education at university or equivalent level had been introduced in several countries, while at the same time the tremendous increase in demand for engineering had highlighted the need to improve the cost-effectiveness of the engineering process itself. The result was a stratification of the engineering workforce into academically trained engineers, technicians (under various labels), draftsmen, and tradesmen or craftsmen. The details and extent of this stratification varied considerably from country to country and also between industries, but the new paradigm was unmistakeable.

The *production period* resulted in a number of changes to the engineering paradigm, some of which had been initiated in earlier periods, and some new ones. In the former group was the further elaboration of the stratification of the engineering workforce. The term “engineer” became more or less synonymous with the academically trained technical person, the *professional engineer*, and the requirements on obtaining the associated title became circumscribed in detail within each country. Driven both by the advances in science and by the engineering activity itself, technology continued its exponential growth and led to further specialisation in the form of engineering disciplines, i.e. civil, structural, mechanical, electrical, electronic, and chemical, and within these even further specialisation into such areas as automotive engineering, railway engineering, high voltage engineering, and nuclear engineering.

As the name of the period indicates, it was not only that the variety of products increased greatly, but the numbers of each product manufactured increased at a rate that would have been unimaginable at the start of the period. This mass production of consumer goods had a significant impact on the engineering profession. Firstly, in addition to the innovation and design of a new product, the design of the production process, including the facility with all its infrastructure and the individual sophisticated and partly automated machine tools, became a major part of engineering work and led to an emphasis on and development of such additional components of technology as reliability, maintainability, and human factors, and with it a further specialisation within the profession. Secondly, the increasingly complex manufacturing machines and processes required highly trained and skilled operators; it was no longer possible for engineers to create the actual products they designed. While engineers used to have some training in basic manufacturing operations, it was not reasonable to expect an engineer to be able to operate a complex, numerically controlled machine tool. Thus, the separation of the engineer from the rest of the engineering workforce became more pronounced and the interface more formalised.

A new feature related to this rise of mass production was the need to maintain this vast collection of engineered products, and in response there arose a whole new classification within engineering, maintenance engineering, and a whole new group of trained and skilled personnel – maintenance technicians.

A new development was the availability of a vast collection of mass produced standard construction elements. As a result, the major part of engineering design became a process of selecting the most appropriate combination of such elements; only a minority of engineers were actually involved in creating new elements and had a need for the associated detailed physics, chemistry, and materials science knowledge. This led to another dimension of specialisation, and an ongoing issue for engineering education.

Finally, and perhaps most importantly for the engineering paradigm, this period changed the role of the *average* engineer from a creative and intellectually stimulating one to that of a cog in the vast industrial complex, "turning the crank" of what became an engineering production process. This diminishing of the role of the engineer and what can only be described as a waste of a precious resource took place at a time when the application of technology was coming under increased scrutiny and criticism for its lack of concern for social and environmental values.

The period in which we currently find ourselves, the *information period*, is witnessing a development which has all the hallmarks of the beginning of a shift in the engineering paradigm comparable to that which took place in the Industrial Revolution period. It is driven by two main factors. One is the advent of cost-effective computing power and the associated new branch of engineering – software engineering. Software engineering is basically different from traditional engineering, with a very different technology (Aslaksen 2009). The knowledge base is more like a branch of mathematics and formal logic, and the resource base consists of reusable software modules. Reliability and maintainability take on completely new forms, and so on. Within engineering there is now a new major interface, between these two branches of engineering, and a corresponding need for integration, which is being provided by the new activity of systems engineering.

But, of greater significance in the context of this paper is the increasing importance of the computer as a tool for engineers; it has become the essential tool in all areas of engineering and the equivalent of the machine tool in the engineering production process mentioned above. This tool is, on the one hand, increasing the productivity of engineers considerably, but, on the other hand, it is changing the intellectual content of what engineers do. A considerable part of engineers' time is spent on learning the language and rules associated with each new application and in keeping up with the frequent version changes. And once learnt, that language and those rules do, in many applications, dictate how the design must be performed. It is through this standardisation, with its ease of communication and data exchange, that much of the efficiency gain is achieved, but it also provides a serious disincentive for creative thinking.

The other main driver is the recognition that the engineering profession does not occupy a position in society that would allow it to realise its full potential with regard to creating value for society. This is due partly to a deficiency in engineering education, and partly to industry's use of engineers, as it developed during the Production period and mentioned above.

3.3 Analysis

From the history of the development of engineering and, in particular, to the role of the professional engineer and the environment in which this role operates, there emerges a fairly clear picture of what we defined as the engineering paradigm. If we recall the three components of the definition, we can obtain the following overview of the development:

Period	Other activities	Relationships	Technology
Ancient	Arts and crafts	Integrated with engineering; no significant professional distinction	Knowledge transmitted verbally and by example. Resources limited to timber and stone, with some metals and simple hand tools
Classical	Engineering, architecture, arts and crafts	Arts are separate from engineering, architecture and crafts start to separate	Written records of designs and of scientific input appear. Resources include bricks and concrete, iron/steel becomes more available
Medieval	Engineering, architecture and crafts/trades	Architecture becomes partly separated from engineering, crafts/trades form guilds.	Slow increase in knowledge base; improvement of existing designs. Increase in mining technology.
Renaissance	Engineering, crafts/trades	Engineering and architecture are now generally separated. Engineering distinct from guild system, but informal (verbal) interface. Increased importance of design.	Expansion of knowledge base due to upsurge in science and printing.
Enlightenment	Engineering, management, crafts/trades. Growth of industries creates a distinction between crafts and (industrial) trades.	Engineering no longer interact with crafts, but is closely related to the trades (as fabricators).	Further interaction with science, improvement in fabrication methods (precision, standardisation).

Revolution	Engineering disciplines, management, capitalist, industrial trades, start of draftsman/technician classification	Design becomes a separate engineering activity, with a formal interface (drawings) to the trades. Importance of business activities.	Rapid increase in all aspects of technology. Formalisation of the technology through education (textbooks).
Production	Engineering disciplines Management Technician/technologist Drafter Trades/operator	Close involvement with mass production and its management, interaction with business activities (sales, marketing)	Very great expansion of the technology; in particular, of the resource base in the form of standard construction elements.
Information	Software engineer Hardware engineer Systems engineer	Increasing social concern about the effects and directions of engineering.	An increasing proportion of technology is becoming related to software.

In terms of all the activities involved in an engineering project, the proportion performed by engineers has been continually decreasing, while the intellectual content of that proportion has been continually increasing. The need for unskilled labour as a source of mechanical energy was gradually replaced by power sources designed by engineers, and within the skilled labour there was a growing division between manual skills and intellectual skills; between training and education. This initial change, and the subsequent further specialisation of manual skills into trades and of the technical activities into levels of intellectual content on the other hand (drafter, technician, technologist, engineer) and into disciplines (architecture, civil, mechanical, etc.) on the other. Because of industrialisation, activities such as business management, sales, marketing, and legal support have taken on an increasing role in engineering projects, and through its interaction with these activities engineering has become more “commercialised” and become more of a commodity, as was pointed out in (Galloway 2008). And, finally, the size and duration of many engineering projects, whether it be a manufacturing project, like the development and production of a new car, or a construction project, such as a new railway, meant that the *impact* of the engineering activity on the outcome was greatest in the early phase of the project. As a result, a *de facto* further stratification was introduced into engineering; the conceptual, strategic, and holistic work as opposed to the detailed, specialised work in the later phases, which also has a certain component of “turning the crank”, as this work is often highly circumscribed by standards. In effect, this amounts to a further stratification according to intellectual content.

In all of these changes to the engineering paradigm there has been, whether explicitly or implicitly, one main principle: the quest for greater cost-effectiveness. This principle is inherent in engineering due to its purpose of being useful, but is reinforced by engineering being embedded in industry. It was discussed in some detail by Dessauer, who called it "Ökonomiegesetz" (Dessauer 1956, p. 286). The cost arises from the length and intensity of the education (both initial and continuing) required to master a given part of technology; the effectiveness is determined by the match between the engineers' capabilities and the work assigned to them. The specialisation and structuring of engineering into more and more, narrower and narrower disciplines and sub-disciplines has been, to a large extent, a means of containing the cost of education and training. The stratification of activities within an engineering project according to the intellectual content of the work has been a response to increasing the effectiveness; for example, it was not effective to have an engineer operate the machine tool to produce the item he had designed, nor is it efficient to have engineers operate the Computer Aided Drafting tools that produce the drawings of their designs.

Our brief historical analysis identified a number of factors that have influenced the development of the engineering paradigm, and they can be considered to fall into two groups. One group contains those factors that led directly to a change in the paradigm in order to maintain or increase the cost-effectiveness; they include such external factors as the formation of guilds, the rise of science, and the development of business as a separate, major discipline with its own body of knowledge, as well as the internal factors arising from the inherent exponential growth of technology. The other group contains those factors that had a more indirect or subtle influence, such as the structure of the society (e.g. China in the period 1680 to 1911 or Japan prior to 1870) and associated relative social standing of engineering profession, philosophical/religious attitudes (e.g. return to nature, technology as environmentally destructive, etc.), and local (national) economics (domination of specific industries, such as mining or agriculture). It is this group of factors that results in local versions of the paradigm.

3.4 Looking Ahead

Predicting the future is always fraught with uncertainty; however, based on the forgoing historical analysis, and the identification of cost-effectiveness as the main driver of paradigm changes, it is likely that we are at the beginning of a significant paradigm change (or, to use the Kuhn metaphor, an engineering revolution). Central to Kuhn's analysis was the use of history to gain an understanding of what something "is"; not "is" as in "current state", but as in "nature" or "essence". It is the thing that evolves, the thing one can identify as remaining throughout the evolution, whereas the paradigm contains the features that change and that thereby describe the individual paradigms. In the forgoing we have identified the creation of value as the core of engineering that remains throughout its evolution, and the position of the professional engineer within the spectrum of actors in the field of engineering as the feature characterising the engineering paradigm, There is a widespread opinion, both within the engineering profession and without, that engineering is not realising its potential for providing value to society. Engineering continues to produce innovative and ever more advanced technology, but does this address the needs of society in the best way? Given the extensive knowledge and experience of the profession, is it having an appropriate influence of the direction of the development of society? Is current engineering education optimised to today's conditions and requirements? Does industry's employment of engineers make the best use of their abilities? These and similar questions reflect a feeling that the contribution of the professional engineer to society has slowed from its previous exponential rise; i.e. that its effectivness is not what it could be.

If we consider the evolution of the role of the "engineer", from craftsman and builder of structures, through machinist, then practical engineer (or technician), then, in the late eighteenth century, the emergence of the academically trained engineer, and then the increasing specialisation in the following two centuries, this evolution seems to have slowed or stagnated. In particular, when compared to the accelerating increase in the body of knowledge. There is, in a number of countries, a distinction between such actors within engineering as engineer, technologist, and engineering technologist. Smith (Smith 1969) distinguishes between engineer, technician, and craftsman, and Sporn (Sporn 1964) distinguishes between technician, technologist, and engineer. However, such distinctions appear to have done little to change the perception (and reality) of what an engineer is and does (Murphy 2012). This is illustrated in Fig.1.

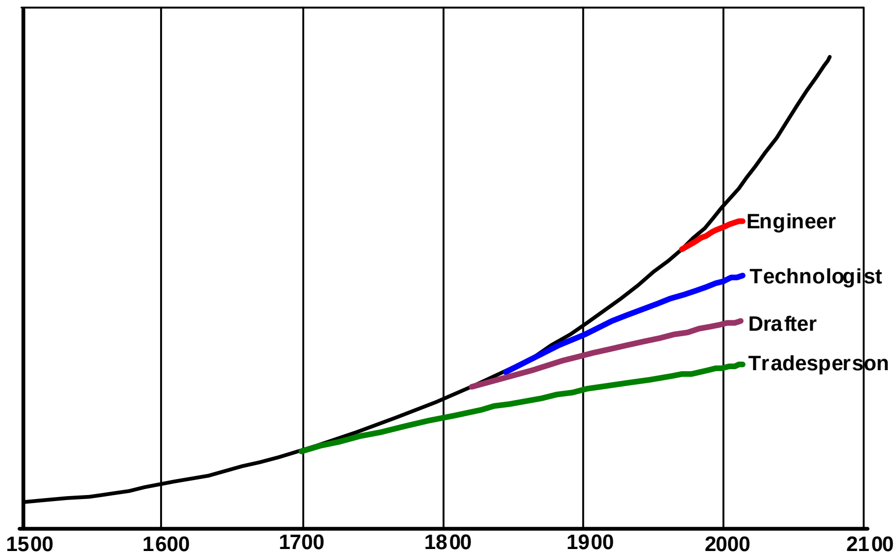

Figure 1 The development over the last six hundred years of one aspect of the engineering paradigm, the structuring of the technical activities within engineering projects by intellectual content (the vertical axis),

In Fig. 1, the vertical axis is intended to be a measure of the intellectual content of the activities involved, or what we might call engineering's value-creating potential.

It is composed of technology (i.e. the knowledge and resource bases) and of all those surrounding, or additional intellectual capabilities that have been identified as crucial enablers in the environment in which engineering takes place. All of these components are evolving at an accelerating pace, hence the exponential character of the curve. In particular, this is important for the engineer, as it is the creative and innovative intellectual activity that is the hallmark of the professional engineer and the part of an engineer's work that creates the greatest value for society. This view of the role of the engineer in society, its value-creating potential, and the obstacles to fully realising it was developed at great length by Dessauer (*op.cit*).

In Kuhn's description, a paradigm shift takes place in science when the body of observations that cannot be explained by the current paradigm reaches a critical size *and* a new theory appears that explains all or most of these observations. It is this triggering effect that led Kuhn to characterise the paradigm shifts in science as revolutions. Looking back at the history of engineering, the paradigm shifts have been much more gradual and could not by any means be characterised as revolutions. However, due to the accelerating pace of the changes to both technology and to society this could be about to change. The body of evidence suggesting that the current version of the professional engineer is not fulfilling the potential for value creation has, as previously noted, been building with increasing rapidity over the last couple of decades (and is corroborated in (Aslaksen 1996)), and a "trigger" that will effect a paradigm shift could well result in something like a revolution. But while in science the trigger is the acceptance of a new theory, in engineering the trigger will be the demonstration that a new version of the professional engineer does result in an increase in value creation. It is not enough to have a vision for such an engineer; it requires the investment to actually produce such engineers (education) and to give them the opportunity to realise their potential (industry), but above all it requires the profession itself, as represented by the Institutions, to promote the change.

The comparison with science and with Kuhn's work can also serve to bring into focus the role played by the Institutions in changing the engineering paradigm. In the case of science, the value, in the form of true scientific knowledge, is produced directly by the scientific community, represented by its Institutions. In the case of engineering, the value is produced only indirectly through industry. But the central purpose of industry is to create financial gain for its owners, and industry's view of how engineering can best contribute to fulfilling that purpose does not necessarily coincide with the definition of the value of engineering put forward in this paper. To a certain extent, the difference between these two views is a reflection of what Marx identified as the difference between "use-value" and "exchange-value" (Marx 1867), or "what society pays for is not necessarily what society needs". Therefore, whereas a paradigm change in science takes place wholly within the scientific community, a change in the engineering paradigm, i.e. the role of the professional engineer within engineering projects, once articulated by the engineering community, requires industry to accept and implement it. The Institutions should be the principal agents in facilitating this acceptance.

What could such a paradigm change, or "engineering revolution" look like? Based on the foregoing discussion, engineering activity would be concentrated in what is today the "front end" of engineering projects. Understanding and analysing the full extent of the problems, with all their interfaces to non-technical (economic, legal, social, political) aspects. Using an in-depth knowledge and understanding of technology to identify possible solutions and evaluating these, including with regard to all forms of risk. Specifying the functionality and performance of selected solutions. Developing and evolving the standards to which these solutions should be implemented.

The implementation of specified solutions, the "production" part of the engineering process, would be performed largely by a new professional group combining the skills of drafter and technologist, utilising computers and software as the new "production" tools. For example, the task of verifying that a detailed design complies with the relevant standards and legislation could be performed completely automatically by software. Also, all the routine tasks associated with managing the engineering process, such as scheduling, resourcing, forecasting, etc. would be performed by this group.

The formal part of the interface between the engineers and the technologists would increasingly be in the form of models. The use of models and the number and sophistication of the associated modelling software packages are on the increase, but in order to suit this new structure of engineering they would need to reflect the division of labour between engineer and technologist and to take into account the very different purposes of the software in the two cases. In the case of the engineer, the purpose of the software is to provide a cost-effective *support* for the intellectual activity that produces the result; in the case of the technologist, the purpose of the software is to *produce* the result, with the technologist in the role of dedicated operator.

This paradigm change will require (or will force) significant changes to the three entities involved. To academia, it will mean a rearrangement of the three components of the syllabus: general engineering knowledge (mathematics, physics, chemistry, biology), specialised engineering knowledge (increasingly narrow specialisation necessitated by the growth of technology), and knowledge about the environment in which engineering has to operate in order to be effective. To the profession, represented by its various professional bodies, a reorganisation to better recognise the value-creating potential of the engineer, and to industry, a more appropriate allocation of work to capability.

References

[1] Aslaksen, E.W (2009), *Why Software is Different*, Newsletter of the Systems Engineering Society of Australia, No.48, July 2009.

[2] Aslaksen, E.W. (1996), *The Changing Nature of Engineering*, McGraw-Hill Australia.

[3] Aslaksen, E.W. (2012), *The System Concept and Its Application to Engineering*, Springer.

[4] Constant, E.W. (1987), *The Social Locus of Technological Practice: Community, System, or Organisation?,* in The Social Construction of Technological Systems, Bijker, Hughes, and Pinch (eds.), The MIT Press, 1987.

[5] Cuomo, S. (2007), *Technology and Culture in Greek and Roman Antiquity*, Cambridge University Press.

[6] Dessauer, F. (1956), *Streit um die Technik*, Verlag Josef Knecht

[7] Floorman, S.C. (1996), *The Existential Pleasures of Engineering,* St. Martins Press

[8] Galloway, P.D. (2008), *The 21st Century Engineer*, Am. Soc. Civil Engineers, Reston

[9] Grimson, W. (2012), *The Open-endedness of Engineering Design: A Review of a Number of Approaches Describing Design with Particular Emphasis on Phenomenology*, Forum on Philosophy, Engineering and Technology, University of the Chinese Academy of Sciences, Beijing, November 2-4, 2012.

[10] Hart, I.B. (1926), *The Great Engineers*, Methuen & Co. Ltd.

[11] Hill, D.R. (1984), *A History of Engineering in Classical and Medieval Times*, Open Court Publishing Company.

[12] Kuhn, T.S. (1996), *The Structure of Scientific Revolutions*, Univ. of Chicago Press, 3rd ed.

[13] LSJ (1940), *Dictionary of Ancient Greek*, Liddell, Scott, Jones, Clarendon Press, also available online at www.perseus.tufts.edu.

[14] Macarthur, D. (1951), "Old soldiers never die, they just fade away", address to joint session of Congress, 19 April 1951.

[15] Marx, K. (1867), *Das Kapital*, vol. 1, sec. 3, 1867.

[16] Murphy, M, M. Dyrenfurth, and G. Bertoline (2012) *Examining the Identities of Engineers, Technologists and Engineering Technologists*, in Abstracts of 2012 Forum on Philosophy, Engineering and Technology, Beijing, China.

[17] Parsons, W.B. (1968), *Engineers and Engineering in the Renaissance*, The MIT Press.

[18] Rolt, L.T.C. (1962), *Great Engineers*, G. Bell and Sons.

[19] Smith, R.J. (1969) *Engineering as a Career*, McGraw-Hill, 3rd ed.

[20] Sporn, P. (1964) *Foundations of Engineering*, Pergamon Press.

[21] Sprague de Camp, L. (1963), *The Ancient Engineers*, Doubleday & Company, Inc.

[22] Turner, R. and S.L. Goulden (eds) (1981), *Great Engineers and Pioneers in Technology*, St. Martins Press.

[23] Vitruvius, M. (20 BC), *De Architectura*, available at http://www.gutenberg.org/files/20239/20239-h/29239-h.htm

[24] White, L.T. (1962), *Medieval Technology and Social Change*, Oxford University Press.

[25] Williams, R. (2008), *Notes on the Underground: An Essay on Technology, Society, and the Imagination*, The MIT Press.