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Discovery – Design – Responsibility

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> THE acatech IMPULSE SERIES

This series publishes analyses and ideas on principles of science and engineering and research-based policy advice. The content of the IMPULSE series is developed by acatech members and other experts before being approved and published by acatech's Executive Board.

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FOREWORD

What are the technological sciences? What are their characteristics and what sets them apart from other scientific disciplines? How did the technological sciences become established and what role do technology and the technological sciences play in our society? As the National Academy of Science and Engineering, these questions are of central importance to us. acatech's thematic network on the "Principles of Science and Engineering" stimulates debate that crosses the boundaries between the disciplines of philosophy of science, philosophy of technology, sociology of technology, history of technology, economics and the technological sciences.

Despite their importance to our society, the technological sciences have hitherto been largely neglected by traditional scientific research. For a long time, the prevailing view was that science should be pure. The technological sciences, however, do not fit into this paradigm. Moreover, the people working in the technological sciences have themselves given little thought to the principles and fundamental questions of their discipline.

acatech provides advice on strategic science and engineering issues to policymakers and the public. In order to do this effectively, we also need to examine our own discipline. To this end, acatech set up the working group that authored this acatech IMPULSE paper between October 2010 and the summer of 2012. Its aim is to encourage discussion of the technological sciences as a knowledge system both within and outside of acatech. The authors have consciously focused on the topics addressed by the technological sciences, the methodologies they employ and their effective contribution to the public debate on technology and innovation. They have intentionally excluded the equally important issues of the history of the technological sciences, their institutional framework and organisational structures and the distinction between engineering sciences and technological sciences. We are fully aware that there is an extremely close link between research and education in the technological sciences as in any other scientific discipline. Indeed, this link is especially important in the technological sciences, owing to their strong relationship to applications and engineering practice. Nevertheless, it was not possible to study this aspect in detail in this particular IMPULSE paper. Instead, the paper focuses on the following two questions: "What are the technological sciences and what is their purpose?" and "What can we expect of them?" With this IMPULSE paper we intend to improve technological scientists' understanding of their own discipline and to facilitate access to the technological sciences for members of other scientific disciplines.

This is the second volume in our new "acatech IMPULSE" series. The publications in this series feature analyses and ideas on principles of science and engineering and research-based policy advice. They are aimed at anyone involved in both the technological sciences and the field of policy advice, as well as anyone interested in the technological sciences and the role they play in our society.

acatech would like to thank both the project group for its unflagging commitment and everyone who contributed to the work and discussions that made this IMPULSE paper possible.

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EXECUTIVE SUMMARY

Humans have been creating technology since time immemorial. However, what sets modern engineers apart from their historical predecessors is that from the 18^{th} century on they began to apply the scientific method to their work, giving it an objective, verifiable and widely reproducible basis. Of course, engineers were not the only ones to do this. Alongside natural scientists, humanities scholars, economists, managers and physicians, they made their own unique contribution to the spread of science throughout the world by subjecting everything they did to scientific criteria in order to enhance safety and increase productivity. All of these activities were dominated by men until well into the 20^{th} century. It is only recently that the barriers to women have started to be broken down. Since even today, however, the majority of engineers continue to be male, we must keep working towards a better gender balance going forward.

What are the technological sciences?

The technological sciences form a discrete and independent group of scientific disciplines with a distinct focus and with goals, methods and institutions which differ from those of other sciences. The focus of the technological sciences is technology, in the sense of artificial, functional objects and processes that possess both tangible and intangible elements. The technological sciences involve the study of technology in terms of its structure and function, its impact on the environment and society and the social and cultural context in which it is developed and used. They thus look at the entire life cycle of technology, encompassing design, manufacture, utilisation, and disposal, waste management or recycling.

The goal of the technological sciences is to generate knowledge about the laws, structure and rules of technology with a view to using this knowledge in technological applications. The technological sciences employ a diverse but targeted array of methodologies ranging from the rational and systematic to the intuitive and heuristic. However, it is fair to say that the technological sciences tend to focus on what is actually feasible rather than what is merely conceivable. The technological sciences are not confined to the analysis of technology – they also develop ways of combining existing technologies to create something new. They anticipate future applications of technological knowledge and how technologies will interact with their environments. As a result, the models used in the technological sciences integrate environmental, economic, cultural and social aspects. The technological sciences have a place both within and outside of higher education institutions. Ultimately, they encompass all the scientifically-based knowledge that we possess about the production and utilisation of technology, its cognitive and practical requirements and its impact on the environment, the economy and society.

The technological sciences may be summed up by the following sentence:

The technological sciences establish the cognitive requirements for technological innovation and the application of technological knowledge, and provide us with a basis for considering the impact and repercussions of technology.

The most important intellectual tools that are needed specifically to apply the scientific method to technology are abstraction and modelling as verified. Wherever possible, technology should be verified by experimentation and testing. However, there comes a point where the size and complexity of the system make it impossible to test it as a whole in a laboratory prior to installation. When physical testing cannot be carried out (this may also be for financial, safety or ethical reasons), it may be replaced by modelling and subsequently simulation.

The concrete nature of technology and the abstract nature of scientific thought are mutually complementary: Abstraction establishes a link between what is as yet unchartered novelty, what is already known and has been scientifically investigated. In the technological sciences, abstraction thus facilitates pragmatic problem-solving in engineering practice. Modelling enables theoretical and empirical appraisal of the behaviour of innovations in applications. Modelling makes it possible to identify and assess key behaviours of systems and to influence them through appropriate design.

The models employed in the technological sciences must possess a high degree of completeness and complexity in order to ensure that their results are of sufficient quality to be useful in practice. At the same time, the technological sciences and technology in general remain areas of conjecture and not fully proven hypotheses, which necessarily leads to uncertainties in the statements which can be derived from them. Indeed, the unavoidable use of incomplete stochastic models is one of the greatest challenges facing practicing engineers today.

The interplay of experience and creativity, systematisation and research means that modelling in the technological sciences is ultimately something of an art form. Targeted abstraction is indispensable for successful modelling. It is this part of the design process which is the special domain of creativity.

Responsibility in the technological sciences and technology

There is always a degree of ambivalence attached to any technology. Those responsible for planning and implementing engineering projects are constantly confronted with the challenge of producing something that can deliver the desired benefits without unavoidable harmful side effects. The difficult trade-off between benefit and harmful consequences according to criteria established by society necessarily replaces the simple demand for benefit without harmful consequences that can rarely be satisfied in practice. This in turn requires an ongoing dialogue with society regarding the goals and consequences of technology. Changes in resource availability and reappraisals of the value we attach to these resources, together with reappraisals of how vulnerable the available resources actually are, lead to a constant demand for technological innovations. Similarly, changing social needs that are constantly growing as technology opens up new horizons require a continuous stream of novel technological solutions.

There can be no doubt at all that the application of the scientific method to technology has been largely responsible for the proliferation of creative solutions and improved safety and reliability of technological products and processes that has occurred in the recent past. Indeed, the science of technology is the most potent tool that today's engineers have at their disposal. Nevertheless, whatever we might do, it will never be a perfect science and mistakes will inevitably be made. It is essential never to lose sight of this fact when designing technology. It is the fundamental responsibility of all scientists, particularly engineers, to review and to retest scientific statements about technology. Engineers have a special responsibility to ensure the success and safety of our technological world, despite technology's inevitable imperfections. At the same time, their professional competence obliges engineers to inform society of any doubts or persistent uncertainties and to be prompt in raising any issues that require immediate input from society or that may do so in the future as a result of potential new technologies. As such, engineers and technological scientists are not just responsible for producing optimally functioning, user-friendly technologies that use natural resources both economically and sustainably. They also have a responsibility to inform society about all the conceivable and feasible alternatives for how the high-tech world might look in the future. Technological scientists and engineers are obliged to preserve the options open for the future.

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1 INTRODUCTION

Humans have been creating technology since time immemorial. However, what sets modern engineers apart from their historical predecessors is that from the 18th century on they began to apply the scientific method to their work, giving it an objective, verifiable and widely reproducible basis. Of course, engineers were not the only ones to do this. Alongside natural scientists, humanities scholars, economists, managers and physicians, they made their own unique contribution to the spread of scientific understanding of the world by subjecting everything they did to scientific criteria in order to enhance safety and increase productivity. All of these fields were dominated by men until well into the 20th century. It is only recently that the barriers to women have started to be broken down. Since even today, however, the majority of engineers continue to be male, we must keep working towards a better gender balance going forward.

Transdisciplinary efforts to promote a scientific understanding of the world have resulted in an expansion of human living spaces and an increase in life expectancy, both of which have occurred at a historically unprecedented rate. There is no doubt that the application of the scientific method to our world has enabled a huge increase in the opportunities available to us in our lives. Despite the inevitable limitations on human knowledge and the range of our actions, and in spite of our continuing inability to live together peacefully over the longer term, the advent of the modern age has nevertheless had a largely positive impact. Engineers played their part in this process – indeed, their contribution is uniquely visible in the world around us and our everyday lives. Today, we consider anyone who lacks access to the achievements of the modern world to be a victim of injustice and relative poverty.

In fact, however, it was not the scientific understanding of the world per se that triggered these changes, but rather the way that it drove technological creativity. After all, rather than simply reproducing what exists in nature, engineers create new things that are not found in the natural world. Whilst it is true that everything they do is governed by the laws of nature and that many of their designs take their inspiration from nature's problems and solutions, this in no way diminishes the autonomous character of engineers' creativity. Although scientific insight makes us aware of potentials and constraints, it does not determine the goals that we seek to achieve through our creativity or the many different approaches that can be taken to realising these goals. As scientific exploration of nature, artefacts, individual behaviour and processes in society created more certitude about the premises and constraints for technology, it opened up a whole new world of technological creativity. In the interest of productivity and safety, the intent was equally to defend against dangers and to create new potentials for action. Thus, the creative aspects of modern technology take it beyond the purely scientific principles on which it is based, while the safety of technology is enhanced by the use of scientific methods to verify engineers' designs.

The creative work performed by engineers requires them to use fragile and finite natural resources in order to meet often controversial and constantly changing social needs. This inevitably results in conflicts between the values and interests of different stakeholders, in which engineers become involved. As members of society, engineers themselves also have a part to play in finding a compromise between these different standpoints. One of their roles in these debates is to come up with proposals and practical ideas for achieving consensus-based solutions to the parts of the conflicts that concern the technological aspects of the world we live in.

Changes in resource availability – and in particular our ongoing reappraisal of the value we attach to these resources – cause a constant demand for technological innovations. Similarly, changing social needs that are constantly expanding with the growing technological potential require a continuous stream of novel technological solutions. Since our natural environment varies with time and place and since people's culturally informed needs cannot be boiled down to just a few basic categories, these technological solutions need to be very diverse. Engineers thus develop and design a diversity of new products and processes that reflect a broad spectrum of interests and values in our society and the way that these change over time, as well as differences between cultures. The choice as to which of these products and processes are adopted is determined by the markets, by planning processes, policy decisions and sometimes also by the courts.

Abstraction and modelling are the most important intellectual tools which engineers use specifically for the scientific approach to technology. It is precisely because the goal of technological creativity is to produce something extremely concrete that abstraction and modelling are essential. In order to produce concrete outputs in a responsible manner, it is first of all essential to think them through as thoroughly as necessary at an abstract level. Abstraction establishes a link between what is as yet unchartered novelty, and what is already known and has been scientifically investigated. Modelling enables theoretical and empirical appraisal of the behaviour of innovations in applications. Both tools, abstraction and modelling, do not precede creative design, they rather support and inspire it. The creation of technology essentially involves imagining what might be feasible and then putting it to the test over the course of the development process. The product or process thus emerges as the result of an ongoing dialogue between design and testing.

In order to deliver successful technology designs, it is essential to ensure that the modelling process takes all the relevant real-world phenomena into account. The design and development process must therefore be based on as complete a picture as possible of how the technology will operate in its natural and social environment. This holistic approach means that engineering and the technological sciences must form part of an interdisciplinary network. Technological products and processes generally tend to be complex and need to operate under many different conditions. Reducing complexity in order to increase precision in technological statements is thus not necessarily always expedient. Since boundary conditions should be taken into account as much as possible, rather than ignored, the technological sciences combine insights from many different disciplines, bringing them together in the engineering process in order to create a holistic problem-solving strategy whose individual steps can repeatedly be verified again.

Like many other professions, engineers have established a specific scientific basis over the past two centuries, seeking to establish and maintain principles that are deeply rooted in the widespread application of the scientific method to the world around us. Extensive similarities of theories and methods have led to a particularly close and productive dialogue between the technological and the natural sciences. However, this dialogue was by no means as exclusive as implied by the overly simplistic term "applied natural sciences". Indeed, the study of human behaviour, economics, the way in which social institutions operate and the cultural influences on people's lifestyles are all equally important in order to enable a valid and potentially successful design and development process. Ultimately, the technological sciences encompass all the scientifically-based knowledge that we possess about the production and utilisation of technology, its practical and cognitive requirements and its impact on the environment, the economy and society.

Despite the broad scope of the technological sciences, however, it is important to remember that the finished products and the way they are used transcend the knowledge that went into making them. In other words, although the technological sciences are an extremely important part of engineering and without doubt constitute its most solid and indispensable cognitive component, they do not fully describe all the tasks and activities undertaken by members of the engineering profession. As a result, the technological sciences are not confined to the realm of universities and other higher education institutions. This report will therefore not only provide a detailed description of exactly what the technological sciences are, but will also indicate where their boundaries as a discipline lie, i.e. the parts of an engineers' work that can be scientifically described but not always scientifically explained. Notwithstanding this, there can be no doubt that the application of the scientific method to technology has been largely responsible for the driving forces putting forward the creative solutions and improved reliability and safety of technological products and processes in the recent past. Indeed, it is the most potent tool that today's engineers have at their disposal.

Nevertheless, however hard we try science-based technology will inevitably always remain imperfect and will never be completely free from error. It is essential never to lose sight of this fact when designing technology. It is the fundamental responsibility of all scientists, particularly engineers, to review and to retest scientific statements about technology permanently. Engineers thus have a special responsibility to ensure the success and safety of our technological world, despite technology's inevitable imperfections.

2 FROM ENGINEERING TO THE TECHNOLOGICAL SCIENCES

Engineers design the human living space and provide humans with devices that augment their natural capabilities. They change the shape and physical composition of the environment, influence the way that natural processes unfold and add to what is found in nature by creating objects from natural and artificial materials. Engineers work with both naturally occurring phenomena such as air, water, minerals and biotopes and with artefacts made from a wide variety of different materials, for example buildings, roads, aircraft and computers.

Technology has had a lasting impact on the way we live our lives. If we had not learned how to use fire or invented the lever and the wheel, then civilisation as we know it could not exist. The telescope, the microscope and the computer all acted as catalysts for the advancement of science, opening the door to new fields of scientific endeavour because they enhanced human beings' innate visual and mental abilities by several orders of magnitude. The railways, the car, the airplane, the telephone, the generator, household appliances, the TV and the computer have all had a profound impact on our everyday lives.

Engineering's object classes and process types have developed to a very high standard over the past few centuries, as have the methods used in engineering projects and the structures of the relevant organisations. This success is reflected in engineers' view of their own profession. Traditionally, engineers have always wanted to use their knowledge and practical expertise to create something useful. It is not only in the present that this attitude has reached its limits. There is always a degree of ambivalence attached to any technology. Those responsible for planning and implementing engineering projects are constantly confronted with the challenge of producing something that can perform the relevant task without unavoidable harmful side effects. Since the ostensibly simple requirement of achieving utility without harmful consequences is something that can rarely be achieved in practice, it inevitably becomes necessary to strike a difficult balance between utility and harmfulness based on the criteria established by society. This in turn requires an ongoing dialogue with society regarding the goals and consequences of technology. Changes in resource availability, reappraisals of how vulnerable the available resources actually are and the Earth's finite capacity to absorb waste all mean that there is a constant demand for technological innovations. Similarly, changing social needs that are constantly growing as technology opens up more and more new horizons require a continuous stream of novel technological solutions.

Over the centuries, engineers have succeeded in making many of humankind's wishes come true. As a result, people have become accustomed to them finding solutions to all their problems, an attitude which is now impacting negatively on the engineering profession. To some extent, technology has become a victim of its own success, since people more or less take it for granted that any problem can be solved by technology, i.e. through the art of engineering. Technological systems are expected to work perfectly and be completely safe. Whilst it may be understandable that the public should have this attitude, it is hardly realistic. Engineering does not deal in the absolute but in carefully thought-out compromises that recognise the fact that we can never know everything. If engineers and society are to weigh up the pros and cons of a technology together, they first need to achieve a common understanding of engineering's limitations and what it can realistically be expected to achieve.

Engineering involves both scientific and artistic elements. Although the design process is based on rational insights, general principles and research findings, it nonetheless remains a process that is mainly guided by creativity. The ability to produce a design, select the right materials or invent a technological process is an individual gift comparable to the unique natural talents of composers, artists and writers. This creative talent is consolidated by studying examples from the history of engineering and through first-hand practical experience.

Society commissions engineers to perform certain tasks, provides the resources for carrying out engineering projects and monitors their impact. Engineers have a duty to identify the external influences on the objects and processes that they have created, to predict how their creations will respond to these influences and to analyze their actual response. For many centuries, these challenges were regarded as part of the creative process and were thus solved intuitively and empirically. Despite early successes such as Archimedes' proof of the Law of the Lever, it would be several centuries before a systematic rational basis was developed for engineering as a whole. It took 300 years to develop classical beam theory after Leonardo da Vinci had initially addressed the problem from a qualitative point of view. Nowadays, it is standard practice for increasingly complex objects, processes and systems to be represented in abstract – i.e. formal and generally mathematical – models that are used to predict, analyse and control their behaviour. Indeed, it would never have been possible to master such complexity without abstraction and the associated generalisations. The advent of the computer, moreover, has given us affordable access to the computational power needed to successfully model complex phenomena.

The origins of systematic scientific thinking in relation to technology can be traced back to the advanced civilisations of the past and to classical antiquity. However, it was first given an institutional basis when technical schools were founded for training engineers to work as public servants, particularly in construction, mining and the military. The French were the first to do this in around 1700, with other nations following suit during the 18th and 19th centuries. The early 19th century saw the establishment of technical schools for industrial engineers which would subsequently become polytechnics, institutes of technology and universities.

This progressive institutionalisation facilitated a continuous increase in the methodological resources made available to the technological sciences through practice, research and education. They thus benefited from advances in physics – in particular mechanics –, chemistry and mathematics, as well as from the greater abundance of qualified engineers who sought to apply the scientific method to every aspect of the technological sciences. Another important step in the development of the technological sciences was the establishment and proliferation of laboratories and experimental facilities that began in the 19th century. These allowed people working in the technological sciences to acquire extensive empirical knowledge that was absorbed by the rules and models used in the field.

As industry became more and more important and the field of engineering became increasingly institutionalised and wide-ranging in terms of the topics that it embraced, engineers found themselves confronted with ever more complex and diverse tasks. Intuitive design and systematic empirical methodologies alone no longer sufficed to provide solutions to the needs of government, industry and society. As a result, the models used in the technological sciences became more and more complex and increasingly started to incorporate knowledge from the fields of economics, the social sciences and cultural studies.

3 THE TECHNOLOGICAL SCIENCES AND THEIR PLACE IN SCIENCE AS A WHOLE

3.1 SCIENCE

Science can be understood from both a cognitive and a social perspective. On the one hand, it involves knowledge systems (the body of knowledge acquired through the scientific method which can also be criticized using this same method), whilst on the other it also comprises knowledge communities (scientific disciplines and institutions).

Science accumulates, codifies and produces theoretical, formal and empirical knowledge. This knowledge is always acquired in specific historical and cultural contexts and can thus ever apply only to selected aspects of the relevant topic. Unlike other types of knowledge such as common knowledge, scientific knowledge is acquired, tested and validated using particularly rigorous methods. Scientific knowledge is obtained in a methodical manner, substantiated in a way that can be understood by others, tested intersubjectively and then incorporated into the existing body of knowledge. Empirical and theoretical findings must be verifiable, whilst experimental findings must be capable of being replicated. Moreover, the underlying premises must be stated and the reasoning and procedures used must be explicitly described. Scientific knowledge should demonstrate both coherence and consistency with regard to the subject in question. It must be validated both through the critical appraisal of the relevant expert communities and in its practical application. The methodological manner in which it is acquired and validated means that scientific knowledge is better-founded (more valid and reliable) and thus more legitimate than other types of knowledge.

The acquisition, testing and validation of scientific knowledge is carried out in different scientific disciplines, i.e. institutions created by the scientific community. New scientific communities are generally created either as the result of a split from an existing discipline or through the application of the scientific method to established practices. They may be focused on understanding recent findings or on helping to solve some of the problems faced by society. Institutionalisation, for example the establishment of scientific institutions, societies and journals, helps to consolidate these scientific communities. It is the scientific system as a whole that determines whether new scientific communities and institutions are accepted or rejected. Moreover, scientific disciplines may cease to exist if the topics that provide their raison d'être lose their scientific or social relevance.

The decomposition of the scientific system into disciplines and groups of disciplines is the product of a dynamic and open-ended historical process. Rather than being sharply defined, the boundaries between the different disciplines shift in accordance with scientific and social developments and the resulting reinterpretations. Today, for example, it is customary to distinguish between the humanities, cultural studies and the social, natural, life and technological sciences. In actual fact, however, these groups of disciplines overlap with each other and individual disciplines can often be assigned to more than one of them.

Groups of disciplines and individual disciplines differ from each other in terms of how they acquire, test and validate scientific knowledge, as well as with regard to the topics they address and their goals, methods and institutions. The humanities are focused on understanding and interpreting the output of intellectual creativity, with particular emphasis on the study of texts. Cultural studies, meanwhile, attempt to transcend the perspective of any individual science by investigating, for example, the overall symbolic meaning of human behaviour and its outcomes. The social sciences study how people live together in society, while economics explores the structures and conditions connected with economic activity. The natural sciences seek to provide a scientific explanation of the natural world and of natural phenomena produced by humankind by uncovering the basic laws of nature and using them to make predictions about how processes will unfold based on known initial and boundary conditions. The life sciences, meanwhile, study the processes and structures of living things.

The technological sciences establish the cognitive requirements for technological innovation and the application of technological knowledge, and provide us with a basis for considering the impact and repercussions of technology.

The scientific disciplines can be subdivided into the epistemologically oriented sciences (sometimes referred to as "pure science") and action oriented sciences (sometimes referred to as "applied sciences"). The first type of sciences is focused mainly on the acquisition of empirical and theoretical knowledge and is less concerned with the practical applications of this knowledge. Their goal is to create a knowledge system that is both coherent and consistent. The action oriented sciences, on the other hand, are interested in knowledge that can be used for practical applications. In other words, the important thing is whether or not the knowledge works in practice, whereas it is not so important for it to be completely coherent and consistent. While the goal of the pure sciences is to achieve as complete an underlying knowledge as possible of the relevant field, the applied sciences are inevitably forced to work with incomplete knowledge owing to the infinite number of different contexts in which the knowledge might be applied. The natural sciences and humanities thus tend to be classified as pure sciences, whilst the technological sciences and medicine tend to be regarded as applied sciences. Of course, all of the sciences referred to above have a theoretical (general principles), empirical (specific propositions) and practical (applications) side. Nevertheless, the characteristics and relative importance of theory, empiricism and practice vary from one scientific discipline to another. It is therefore not possible to unequivocally assign the different groups of scientific disciplines to one or the other of the two categories of "pure" and "applied" science.

3.2 SPECIFIC CHARACTERISTICS OF THE TECHNOLOGICAL SCIENCES

The technological sciences form a discrete and independent group of scientific disciplines with a distinct focus and goals, methods and institutions which differ from those of other sciences. The core technological sciences are surrounded by a group of subdisciplines that overlap with other groups of disciplines. Thus diffuse "boundaries" exist with other disciplines and groups of disciplines such as biotechnology, information science and some of the applied natural sciences. Sciences have mutually beneficial relationships by sharing theoretical concepts, methodologies and empirical findings. As a result of this sharing process, any given science can act as an ancillary discipline to any other science. Finally, it also true that many concrete development tasks can only be solved through an interdisciplinary approach. For example, machine speech recognition requires cooperation between the fields of information science, acoustics and linguistics.

The *subject* of the technological sciences is technology, in the sense of artificial purpose oriented objects and processes that possess both tangible and intangible elements. The technological sciences involve the study of technology in terms of its structure and function, its impact on the environment and the social and cultural context in which it is developed and used. They thus look at the entire life cycle of a given technology, from design and manufacture through to utilisation and disposal or recycling. This overall context is often rather imprecisely referred to as technology (see Chapter 4.1). The subject of technology is distinguished by a high degree of complexity. This results from the diversity of technology, from its socio-cultural and economic embedment and the numerous contexts that this gives rise to. Time is another factor that adds to complexity, since in some cases the individual steps of technological activities can stretch over long periods of time.

Technology is an intrinsically human phenomenon and pervades every aspect of our lives. It is therefore hardly surprising that in addition to the technological sciences there are numerous other disciplines that also deal with technology. These disciplines specialise in particular aspects of technology, such as the philosophy, history and sociology of technology, as well as disciplines that incorporate technology into many aspects of their work, for example economics and ergonomics. The technological sciences, on the other hand, focus explicitly on technology *per se*. Their goal is to develop new technologies and they employ a specific methodology in order to do this. This differs from most of the other disciplines referred to above, where technology is just one among many of the topics addressed.

The *goal* of the technological sciences is to generate knowledge about the laws, structure and rules of technology with a view to using this knowledge in technological applications. In other words, they seek to provide explanations and practically-oriented knowledge that can be used for a specific purpose in technological practice. Broadly speaking, empirical and theoretical work in the technological sciences is geared towards increasing the scope of what is feasible in technological practice. The technological sciences anticipate future applications of technological knowledge and how technologies will interact with their environment. As a result, environmental, economic, cultural and social factors are integrated in technological models (see Chapter 4.2). Knowledge about the rules of technology encompasses end-means relationships and thus includes implicit or explicit practical guidelines (see Chapter 4.1). Technological knowledge also includes conjectures about a technology's function, which in turn have implications regarding its goals and purposes (see Chapter 4.1). Validity is claimed for the statements of technological science in the context of specific applications – ultimately, they must stand the test in practice.

Many other sciences are more concerned with cognition *per se* rather than the application of their findings. Of course, the technological sciences also pursue the goal of making new discoveries, but they always do so with a view to eventually finding practical applications for them in some shape or form (see Chapter 5). Furthermore, the technological sciences also engage in concrete development work, although they do not generally develop a technology up to the point where it is ready to be marketed. Instead, the goal of this concrete development work is to evaluate or demonstrate a particular set of findings. The pronounced focus of the technological sciences on activities is also found in other disciplines and sub-disciplines such as medicine and some branches of sociology and economics, although the areas of activity that these fields focus on are very different.

The technological sciences employ a diverse but targeted set of *methodologies* ranging from the rational and systematic to the intuitive and heuristic. They have no hesitation in borrowing methods from other groups of scientific disciplines such as economics and the natural and social sciences. In particular, they have adopted the natural sciences' strategies for devising a formal, mathematical approach, as well as some of the principles of innovation theory used in economics and the social sciences. In addition, the technological sciences generate their own knowledge about the rules governing technology through specific experiments, tests and simulations (see Chapter 4.3), as well as distilling the experience gleaned from the practical application of technology. The technological sciences are not confined to the analysis of technology – they also develop ways of combining technologies to create something new.

As a rule, individual sciences do not have a monopoly of particular methods. Instead, standard scientific practice involves sharing methodologies with other disciplines or adapting general methodologies to the specific requirements of a particular discipline. One general characteristic of the methods employed by the technological sciences is the emphasis of its models on capturing the full complexity of the subject being investigated to a greater extent than in many other sciences, especially the natural sciences. Another feature is the heterogeneous nature of the knowledge incorporated into the models. This complexity and heterogeneity exhibit some parallels with e.g. the study of history, although the knowledge in this latter field is much less formalised than in the technological sciences. Another specific characteristic that the technological sciences share with other applied sciences such as medicine is the significant role played by models in bringing different types of knowledge together. The key problem is how to integrate diverse bodies of knowledge from different sources into models that accurately reflect the complexity of the subject being investigated and the associated questions and goals. The models employed in the technological sciences must maintain a high degree of holism and complexity in order to ensure that the results they generate are of sufficient quality to be used in practice. At the same time, the nature of the technological sciences and technology in general is such that there will always remain a certain degree of conjecture and matters which are not hard facts.

Most sciences have a structure based on scientific *institutions*, i.e. global bodies and regulatory frameworks. Whilst this is also true of the technological sciences, the relevant institutions are characterised by significant overlaps and extremely close relations with other sciences and with those involved in the practical application of technology. As well as being found in universities, other higher education institutions and non-university research institutions, the technological sciences' institutions are thus also found in industry. The technological sciences train engineers, their research findings are used by engineers in their day-to-day work and the models employed by the technological sciences incorporate practical experience derived from the use of technology. Similar overlaps between theory and practice are also found in other fields, such as law and medicine. These applied sciences have respectively succeeded in combining technological science with the art of engineering, legal theory and legal practice, and medical science with the skill of the physician.

The tasks of the technological sciences can be summarised as follows:

1. The technological sciences investigate the processes and develop the methods to be applied and implemented by engineers. Only with these methods it is possible to use modelling and model-based simulations to assess in advance their deployment how well complex systems will function and, for example, to gauge their impact on the environment.

2. The technological sciences assess existing complex systems' suitability for the solution of widely socially recognised problems and investigate the associated scientific fundamentals.

3. The technological sciences help practising engineers to select system components and to assess the service life and safety risks of these components.

4 DISCOVERY IN THE TECHNOLOGICAL SCIENCES

The technological sciences involve theoretical and empirical research as well as design-oriented and application-oriented practices. As in many other sciences, the boundaries between these two domains often became rather blurred during the second half of the 20th century. The traditional distinction between basic research which was more highly regarded and applied research viewed to be of lower rank, has tended to disappear both at the institutional and methodological levels and in scientific and research practice. The natural sciences have become more technological and technology has become more scientific.

An additional phenomenon can be observed for all disciplines: any given discipline can act as an ancillary science to any other discipline. A ranking of any type is obsolete. The boundaries between disciplines are thus fluid, and different fields can play a more important role in research, education and development, depending on the specific circumstances. The order in which these different fields are brought in during the course of projects in the technological sciences can also vary. Nevertheless, application and design remain the core priorities. Ultimately, the technological sciences develop the knowledge required for concrete design work and the practical application of technology.

4.1 THEORETICAL AND EMPIRICAL KNOWLEDGE IN THE TECHNOLOGICAL SCIENCES

All of the technological sciences' disciplines involve theoretical, formal and empirical knowledge. The idealised approach described in many textbooks is as follows:

> confirmed rules → prediction → experiment → anticipation of possible technical functions → observations and first trials → prototype → test → verification → feasibility prediction → implementation → validation in practice

However, this is only one of many approaches that may be taken in the technological sciences. Many of these steps are performed iteratively and/or in feedback loops, while some are missed out completely. It is not usual to work through the entire sequence from beginning to end, whereas it is by no means uncommon to start somewhere in the middle. The point at which a project begins in the technological sciences depends on the issues and concrete problem being addressed. In order to design technology, it is necessary to know the relevant technological functions. However, the technological functions are often discovered through trial and error during the first attempts at producing a design and are only consolidated through abstraction at a later stage. Conversely, technological functions and rules can be extrapolated from knowledge of the laws of nature, albeit not through pure deduction alone. A successful application of tried-and-tested rules can be indicative of underlying laws, but should not be equated with proof.

The technological sciences address both existing technology and technology that is either planned or at least believed to be feasible. Empirical and theoretical knowledge in the technological sciences is necessarily complemented by knowledge from the natural and social sciences and the humanities – after all, the design of technologies is subject to limitations imposed by the laws of nature and by the social context in which all technologies are ultimately used. It is how technology fits into this context that is investigated by cultural studies, the humanities and the social sciences. For the purposes of this report, the social sciences are taken to include both economics and law. These disciplines are extremely important for understanding the problems that arise in connection with the direct and indirect impacts of the discoveries and creations of the technological sciences – for example ethical questions and issues relating to the acceptance and abuse of technology and the justification of how it is used.

The theoretical knowledge is expressed as *law-like* statements analogous to the laws of nature, while *fact-like* technical phenomena, organisational phenomena and phenomena from the realm of the social sciences are expressed as statements about rules. Although both types of statement use the "if ..., then ..." (A → B) structure, it does not follow that one can be derived from the other. If statements of either type are used to make predictions, they are generally deduced from theory and refer to the state that an object will be in at a particular point in time. These assumptions about future states are descriptive in nature. As explicit explanations of phenomena, they are built on explicit cause and effect relationships – in other words, they can subsume individual phenomena under a law or rule.

When used as basis for the practical application of technology, knowledge no longer takes the form of laws as defined above. Instead, it is expressed as rules such as "In order to achieve B, you need to do A" (which can be abbreviated to "*B per A*"). This can also include instructions for activities, program statements, warnings, etc. The important thing about these statements is whether or not they are effective in practice – unlike statements arrived at by deductive reasoning, they no longer express absolute truths. In other words, what matters is not whether the knowledge is correct, but whether it actually works in practical applications and implementations.

Purely descriptive statements about our experience of what is technologically feasible are not enough to provide a basis for the practical application of technology. New discoveries are made with the assistance of e.g. simulations, experiments and tests (see Chapter 4.3). Rather than employing purely deductive reasoning (applying general laws to specific cases), these fields use abductive reasoning, where specific features are used to make an inference about the validity of general properties. Although this is not an accepted form of logical inference, it does enable certain assumptions to be made about how a technology might function. These assumptions then need to be verified, since they have not been arrived at by sound deductive reasoning. Since knowledge in this field is based on concrete end-means relationships rather than on causal relationships, it is ultimately partly prescriptive – rather than being purely descriptive, it is normative, since the goal is always accompanied by an evaluation of the outcome.

In the technological sciences, a theory is a collection of explicitly describable rules that are connected to each other, have proven to be effective in tests and are consistent with each other in terms of their effectiveness. A theory can be broken down into a substantial level and an operative level. The substantial level describes the rules that are connected to each other by the theory – for example the rules for building a microscope or an airplane. Sticking with the same analogy, the operative level of the theory provides rules about how to use a microscope or optimise an airplane. A theory that encompasses both levels is often referred to as a technological theory, and this term is sometimes abbreviated to just "technology" (see Chapter 3.2). Such theories always contain both substantial and operative elements.

The field of design seeks to put rules into practice to enable the design of new technologies and the use of existing or proposed, i.e. prospective technologies. Taking effectiveness as a given, the key factor in this field is the cost-benefit ratio, i.e. the efficiency. This includes ensuring that the technological function is fulfilled for a sufficiently long period of time. It can also be described as experience of using the technology, or empirical knowledge. The hypotheses in this context relate to the technology's capabilities and technological functionality. More specifically, they comprise conjectures concerning its feasibility and manufacture. The statements derived from these hypotheses are possibilistic-normative in nature, e.g. "It must be possible to put into practice x in order to perform function y". The structure of knowledge in this area is partly explicit, as expressed e.g. in guidelines, standards and specification sheets. This explicit knowledge can be incorporated into a technological science theory. However, the knowledge is also partly implicit insofar as it involves applied skills that are difficult or even impossible to express or write down in words, thus hindering its theoretical verification. Moreover, any assessment of a technology's effectiveness (how well it performs its technological or organisational function) must always take account of its intended and unintended side-effects.

4.2 MODELLING

Models play a central role in the technological sciences. Different types of models are employed to describe sets of circumstances and their environment, to design objects and to depict, predict and control their behaviour when exposed to external influences. In addition to the structured acquisition, storage and presentation of information, models are also used to master the complexity of environmental conditions and human behaviour.

There is a long tradition of using physical models in architecture and engineering. Large-scale models of churches were employed in the Renaissance to help visualise their design, thus supporting both the architects and their ecclesiastical patrons in decision-making. Precisely crafted metre-high wooden models were used by carpenters as a blueprint for complex church spires and bridges. The geometric models of the 19^{th} and 20^{th} centuries, on the other hand, were the product of two-dimensional sketches on the drawing board. The use of descriptions and calculations to complement these models enabled the transition from concrete geometric models to abstract physical models that were also capable of predicting mechanical behaviour. Today, computers running the appropriate software enable highly developed models capable of providing a very close approximation of reality across all the different fields of engineering.

Fundamentally, modelling involves the construction of models using standard components and general rules. It encompasses concepts such as selection, classification, creating images, transformation and simplification. These concepts are used to structure engineers' knowledge about the natural environment and artificial objects and sometimes to express it mathematically. They allow general rules to be established and processes to be broken down in order to structure the complex phenomena involved in engineering. Qualified engineers are not only enabled to map the objects and processes that they are designing onto models, but also to incorporate systematically the systems of the living environment. Models enable the systems' key behaviours to be identified, analysed and controlled through appropriate design features. In the technological sciences, abstraction thus facilitates pragmatic problem-solving among engineering practitioners.

The features and content that define a usable model are determined by the practical requirements of engineers. They are described below from the professional engineer's perspective in order to illustrate how the models developed by the technological sciences meet these different needs.

Models always involve modelling something specific for a specific purpose. Modelling can employ the system description concept according to which a system is composed of various elements or subsystems, the way that they behave and the system's structure, i.e. the way that the different subsystems are connected to each other. Systems are conceptually separated from their surroundings by a system boundary and their interaction with these surroundings is determined by the specification of input and output values. This conceptual approach is extremely useful for modelling properties and processes whose characteristics are predominantly determined by combining basic components with clearly defined behaviours. The key step in any modelling process is the separation of the given set of conditions that we wish to change – i.e. a specific aspect of the world – from the content of their environment. A very broad definition of the term "content" is used in this context. It embraces e.g. objects, events, structures and their attributes and interactions, but also ideas, decisions and judgements. Models use abstracted attributes, methods and boundary conditions to represent the actual attributes and processes of the conditions and environment in the real world.

The decision as to what is included in the model and what is left out is thus always up to the person who builds the model. The modeller draws on concepts from systems theory (mathematics, cybernetics, control, structure, behaviour, etc.) in order to describe a system composed of specific aspects of the current, planned or imagined reality (in this context, the focus is on technology in the widest sense of the word). The models employed in the technological sciences differ from the purely descriptive theoretical models used in physics insofar as they are much wider in scope, incorporating ideas, evaluations, decisions and goals.

Models represent the content of situations as objects and processes with specific attributes whose behaviour follows prescribed and quantifiable rules. This means that the model can be used to compute the interactions between the objects and the resulting events in the relevant processes. The influence of the environment on the behaviour of the current situation and planned artefacts is described in the model using predefined boundary conditions. Examples of such boundary conditions are loads and supports for structures and machines. A model's behaviour at a given point in time may alter its future boundary conditions. For instance, supports of structures which are active under compressive stresses may become inactive if tensile stresses occur due to eigen-vibrations. This change in the boundary conditions changes the behaviour of the structure. No such boundary conditions exist for the situations and their environments, since they form a unit in the real world. The boundary conditions included in the model are either selected at the modeller's own discretion or stipulated by the relevant standards.

The degree of abstraction varies from one model to another. If a model fails to incorporate a phenomenon that has a key influence on the behaviour of the conditions being modelled, the model will be largely inadequate. Experience has shown incomplete models to be at the root of many serious engineering accidents. A case in point was the failure of the Barrage de Malpasset arch dam near the town of Fréjus on the French Riviera. In 1959, the dam was completely destroyed when its left abutment collapsed. The cause of the disaster was a build-up of water pressure in an underground tectonic fault that did not lie directly beneath the dam wall and had not been detected at the planning stage. A wall of water 40 metres high killed more than 400 people, destroying two small villages and causing extensive damage to the town of Fréjus.

The technological sciences need to take into account the contexts that the technology they produce will subsequently be used in. Therefore the engineer's role involves more than simply predicting individual variables as accurately as possible within precisely defined boundary conditions. Instead, the technological sciences must equip engineers with the tools they need to make it as certain as possible that the objects and processes they design will be both usable and safe under all external influences to which they are exposed. When taking their decisions, engineers must remember that they can never fully know what the operating conditions will be and that their specification in a model is an assumption. It is thus important to describe the interactions between a model's internal behaviour and its boundary conditions in as much detail as possible.

Modelling is usually done prospectively. Rather than beginning by creating a model of an existing piece of technology in order to perform evaluations or rate its reliability, the starting point for a model is the object that the engineer wishes to design. Consequently, one of the tasks that the technological sciences need to perform prior to and during the creation of a piece of technology is to produce formal – in most cases mathematical but sometimes also intuitive – and easily understood engineering designs that can be combined with the relevant theory to enable an abstract simulation of the model's behaviour. For any given model, a whole host of potential different engineering designs of varying degrees of complexity need to be taken into account. In addressing this task, the role of the technological sciences remains descriptive insofar as it is oriented according to existing models, i.e. the current state of the art of the technology in question. However, the technological sciences can also adopt a prospective approach that would necessarily be prescriptive in nature. This involves developing formal, scientific engineering designs and the associated theories and suggesting them as a theoretical basis for the design of objects and processes or models thereof. This is in fact the point at which theory meets design. The idea is to produce engineering designs that are as "rational" as possible – in other words, to design, build and deploy objects that have a good chance of being successful, and to develop theories for assessing the prospects of reaching the desired goals. Thus, the design task is already present in the background as a guiding principle.

There are of course certain engineering tasks that can only be solved by analysing a system's dynamic behaviour. Consequently, recent decades have witnessed the development of computer simulation as a successful, standalone prospective modelling technique particularly suited to modelling processes. Computer simulation employs special programs to provide predictive virtual visualisations of processes, i.e. dynamic sequences of events, under different sets of boundary conditions. One example would be modelling the loading of a structure as a result of the ground vibrations produced by an earthquake. The purpose of simulating a system is to identify the key characteristics of behaviour that are required to enable its implementation and to prearrange these features on order to achieve the desired goals (including the prevention of unintended side-effects). The principal problem associated with simulation models is the selection of the suitable set of time histories for the boundary conditions and the identification of behavioural features by analysing the results of the simulation. Today, simulations are used to visualise everything from purely technological alternatives and alternative dynamic systems to the ageing process of e.g. machines. There have even been some attempts at predicting potential social impacts, although these are still very imprecise.

The results produced by modelling – and this is also true in a very general sense – are not only highly dependent on the modeller's knowledge of the original of the model and on the available data. They are also extremely sensitive to the (frequently computer-assisted) modelling techniques available to the modeller and which of these techniques the modeller is familiar with. For example, the formal similarities between software engineering and the traditional steps involved in classical engineering design are surprisingly high. It is perfectly conceivable that selective availability could lead from a preference for particular tools to particular preferences with regard to the modelling process.

To what extent are models capable of fulfilling their purpose and accurately representing the things being modelled? It is possible to develop adequate models for representing many artificial objects, since their behaviour is governed by established physical and chemical laws, their shape and physical composition is derived from knowledge of these laws and they are made from artificial materials under controlled conditions. Nevertheless, even the knowledge used under these circumstances remains incomplete. As demonstrated by the "moose test" in the automotive industry, weak points in models of artificial systems are also due to varying goals and contexts of use. The key is to identify all relevant boundary conditions and achieve an adequate understanding of the technological, social and organisational variables such as user behaviour, ways in which the system could be abused, energy, waste and spare part management, and preventive maintenance scheduling. This full range of additional technological and organisational structures (co-systems) required in order for a technological artefact to function properly can be described as its organisational envelope. It is thus clear that even for familiar artificial objects, producing a complete model is something that can be aspired to, but not guaranteed.

As a rule, models with a high proportion of natural components tend to be far less complete. Arch dams are once more a case in point. A significant proportion of the deformations that determine the dam wall's structural behaviour occur underground due to the weight of the stored water and the seepage flow. Tectonic faults and geological layers with low material strength can constitute potential weak points. Even thorough and costly geotechnical surveys are not enough to provide absolute certainty about the nature of the underground conditions. Likewise, dynamic modelling of moving machinery is not yet able to provide anything more than an approximation of reality, among other things because the damping parameters at the contact points between components and indeed within the materials can only be determined empirically by experimentation. It is impossible to calculate them in a physically and mathematically exact manner and in any case they are constantly changing while the machine is in operation. Models are also used to investigate the operation of technological systems by human beings with a view to reducing the number of accidents, for example.

One further problem is how to combine diverse bodies of knowledge from different sources into models that adequately reflect the complexity of the subject being investigated and the associated questions and goals. A project to develop a toll system, for example, is influenced not only by the current state of the art of sensor, data and software technology and science, but also by organisational, economic, political and legal requirements. The models used in the technological sciences must be highly comprehensive and therefore complex. However, this very fact also makes them more prone to uncertainties in their predictions. Ultimately, this interaction of experience, creativity and scientific disciplines turns abstraction-based modelling in the technological sciences into an art.

The need for sufficiently complete models is a particularly important demand on for the technological sciences. Unfortunately, however, there is no absolute yardstick for measuring completeness. One example of how models must inevitably be incomplete involves modelling the behaviour of man-made structures during earthquakes. In this scenario, the foundations of the load-bearing structures are subjected to primarily horizontal acceleration forces triggered by complex stochastic events. These include the release of energy at the epicentre of the earthquake which subsequently is transferred through different types of geological strata, surface waves and the interactions between the man-made structure and the ground on which it is built. It is simply not possible to fully describe these processes using deterministic models. Since stochastic models are necessarily incomplete, we are left with the concept of unavoidable residual risk.

Pressure to deliver sustainable solutions has led engineers to think in terms of the life cycles of the artefacts and processes that they create. It is no longer enough to model and study systems' behaviour at the beginning of their service lives, since the status of the artefacts and processes described by the models varies over time. On the other hand, we are not capable of seeing into the future, meaning that it is also not possible to guarantee a model's future completeness. The changes undergone by a machine during operation – for example wear and tear or surface fatigue at the contact points – alter the machine's behaviour. These factors have to be estimated by engineers. Doing so also involves predicting the remaining service life and reliability of machinery suffering from wear and tear and fatigue. The technological sciences are expected to develop reliable models for processes that take place over long periods of time. However, the incompleteness of the models should not lead us to the conclusion that they are unusable. On the contrary, in order to ensure that the unavoidable residual risk is as low as possible, it is necessary to represent all identifiable factors as accurately as possible. A model can be said to be usable as long as its behaviour in response to the identified factors and under comparable circumstances does not differ significantly from the actual, real-world behaviour of the artefacts and processes.

The unavoidable use of incomplete models is one of the greatest challenges that engineers have to confront in their day-to-day work. The basic scientific methods employed to tackle this challenge include stochastic models, risk analyses and decision theory techniques. Systematic investigation of possible scenarios and the influence exerted by different phenomena on these scenarios allows an idea to be gained of the relative importance of the different factors. For this to be possible, however, the model must be adequate for the desired purposes. One of the features of innovation is that sufficiently complete models always remain to be developed. Were it not for the technological sciences, the residual risk caused by incomplete models would today be unacceptably high for many engineering challenges.

In addition to engineering's symbiotic relationship with the technological sciences, there are several other factors that influence its success. The majority of these factors derive from the relationship between engineers and society and are connected with aesthetic, ethical, political, economic, financial and legal considerations. Changes in society inevitably also lead to changes in engineering.

4.3 EXPERIMENTATION AND TESTING

Technological knowledge often comes in the form of factual knowledge that– as long as it doesn't incorporate any elements of law-like knowledge – describes individual cases or events. Individual cases and events provide the basis for the development of law-like statements (explanatory knowledge that is causal and practical in nature) through inductive reasoning. However, they also constitute the trigger and key driver of activities. Factual knowledge about the world is acquired through experimentation and operational experience. Knowledge acquired through experimentation can be described by a theory that contains hypotheses expressed in statements such as "if x is true, then y is true" or "y applies to all cases of x" (universal truths).

The **experiment** is the key concept in investigations that are conducted empirically and based on theory. Theory-based experiments require the creation of conditions under which a concrete prediction can be derived from a law-like statement or hypothesis. An experiment begins by creating or setting in motion the initial and boundary conditions of a process, with all the inevitable imprecision that this entails. The process is then observed as it unfolds. The observations are subsequently compared with a prediction which can be "calculated" from a knowledge of the initial and boundary conditions and the relevant law – i.e. a context that describes the process's behaviour and how it changes. The conditions for setting up the experiment correspond to the initial and boundary conditions for a dynamic solution with the help of a calculus, whilst the process and the observations correspond to the calculation of the dynamics and the numerical determination of the result. The empirical approach can therefore prove law-like statements to be false if there is a mismatch between the observations and the theory-based prediction.

In terms of providing a foundation for technological practice, the establishment of the boundary conditions corresponds to the integration of existing basic components that already function in order to create a whole which can then be tested to see whether it can perform a specific desired technological function. As such, it is necessary to distinguish between experiments and tests. Theory-based experiments use theories (expressed as hypothetical knowledge in the form of conditional "if...then..." statements) and in principle replicable combinations of initial and boundary conditions in conjunction with observations to instigate processes in the expectation that these processes will themselves behave in a replicable manner based on the experimenter's knowledge of certain assumed laws. Experiments are certainly a part of the technological sciences, since they also deal with natural processes. By creating replicable initial and boundary conditions, it is possible to instigate specific processes for which the underlying laws are unknown but for which a certain degree of regularity is suspected. These experiments, which are only conducted with artefacts, can be denoted as technological experiments.

When **tests** are used as substantiation for technological practice, on the other hand, assemblies, components, etc. are tested to see whether they can perform certain functions. These functions, together with the initial and boundary conditions, have been surmised by the person performing the test, based on a rule that has been discovered. The rule being tested describes an assumption about a technological function. In other words, the focus is not on a natural or induced process or sequence of events but rather on whether the rule being tested is effective in practice. The question is thus whether the implementation of the technology or the combination of functions achieved by integrating different components has successfully delivered the desired results. Where experiments in the technological sciences perform measurements, technological tests carry out quantitative evaluations of the fulfilment of functional criteria. Meanwhile, whilst the results of an experiment are interpreted in terms of whether they confirm a prediction made by a scientific theory, a test of a technological theory assesses the extent to which all the functions specified prior to the test have been fulfilled in the framework of a theory concerning the subject of the technology's purposes or a whole class of purposes.

Technological tests thus investigate whether a specific arrangement or assembly of components can perform a predefined function, whereas generalization is not intended. Experiments, on the other hand, investigate theories or rules to determine the extent to which they stand the test or the probability that their predictions do in fact occur. In other words, attention is primarily centred on the possibility of generalization.

As long as the full set of initial and boundary conditions have been properly created (including the sequence of actions to be performed on the artefact), a test is considered to be effective if the desired function is successfully fulfilled. This does not necessarily require it to be possible to predict every stage in the process. Nevertheless, it is not sufficient to test a single event, since technology is normally deployed in a social context where it is used repeatedly. It is necessary to guarantee its reliability by ensuring that its construction and functionality can be replicated. A singular successful test thus provides no more "proof" than a singular failure.

If a rule proves to be reliably effective, it can be employed on a frequent and repeatable basis. However, no rule is one hundred per cent effective every time it is used. Just because a test fails does not mean that the rule is not effective. Thus, tests do not seek to discover whether a singular effect can be subsumed under a law. Instead, they seek to verify whether an implementation of a law actually works in practice and delivers the desired results. This also requires the test object to have been implemented in practice before the test begins, since otherwise it is not possible to test its effectiveness.

Example 1: Experimental procedure.

Observations of the fluctuations in the electric charge of solid objects have led to the hypothesis that a boundary layer forms in a transition from a p-type to an n-type semiconductor that shrinks or grows depending on the direction of the current. This hypothesis is used to make a prediction for certain types of doping and crystal dimensions. The experiment recreates the theoretically assumed or selected boundary and initial conditions in the real world (by creating a p-type to n-type transition) and measures the current strengths, voltages and electrical charge transfers. By comparing the observed and predicted values, it is possible to draw conclusions about the validity of the hypothesis, for example with regard to the thickness of the boundary layer or asymmetric transmission during electrical charge transfers.

Example 2: Test procedure

Based on the hypothesis that the poorly conductive layer between a p-type and an n-type semiconductor shrinks or grows depending on the voltage direction, the functional conjecture is formulated that it is easier for electricity to travel in one voltage direction than the other, thus making it possible to achieve a rectifier effect. The decision is therefore taken to build a p-type to n-type transition into a circuit in which alternating current (AC) is converted into direct current (DC), using this arrangement to replace e.g. a vacuum tube diode. The rectifier effect of the new arrangement will then be measured. If theoretical knowledge about the process is available (e.g. about electrical charge transfer in semiconductors), an attempt can also be made to make predictions and compare them against the results of the test. However, this theoretical knowledge is not essential in order to ascertain the effectiveness of the rule: "*p-type to n-type transitions can be used to convert alternating current into direct current*".

There is, however, one methodological limitation. It is often not feasible to test large-scale technological systems after they have been built or installed. Beyond a certain size, it is no longer possible to fit the entire system or the complete device into a laboratory so that it can be tested prior to entering service. There is thus no alternative but to trust that the reliability of the components and the fact that they have been assembled in a tried-and-tested manner will result in a reliable overall system. However, it is only possible to be certain of this by testing the system *in situ* during a trial run. The problem of how to test large scale systems (problem of scale) has yet to be adequately investigated in the technological sciences. Should a physical test not be possible on economic, safety or ethical grounds, then a simulation can be performed instead if a suitable model exists. However, the requirements for ensuring usable simulation results vary significantly from one field to another.

5 DESIGN IN THE TECHNOLOGICAL SCIENCES

5.1 THE TECHNOLOGICAL SCIENCES AND TECHNOLOGICAL PRACTICE

Whilst design is a matter of technology, the study of possibly alternative design is a task for the technological sciences.

There are many different ways in which a technological or techno-organisational function can be implemented. You can use either a handle or a knob to open a door; both perform exactly the same function. There is nothing about the physical, technological and organisational conditions, that requires one design or the other – strictly speaking, the design cannot therefore be "derived" from these conditions. When it comes to design, the technological sciences always have to address a wide range of alternatives. Design is an area where there is particular scope for creativity, but it is also the area where social norms and values have a direct impact on the way that a technology is developed.

The technological sciences attempt to provide appropriate theories to assist individual engineers in developing models of the artefact (as a technological object) or working with existing models of it. The technological sciences support the development of proposed designs. However, whether or not these designs prove to be successful is something that only becomes clear when the technology is used in practice. The task of investigating alternative designs is subdivided into model synthesis, model analysis and model optimisation, depending on the position of the model in the design process (design chain).There are, however, many other model functions, i.e. purposes for which models can be created and used. In this context, it is important to distinguish between purely descriptive models and prescriptive models that can be easily converted into instructions for building something.

As far as **model synthesis** is concerned, the main support that the technological sciences can offer is to provide as complete as possible a catalogue of theoretical ideas about objects that might be created together with theories that are relevant to solving the associated problems, and by developing processes for assembling artefacts. It is important to take account of all the secondary conditions that might have a significant influence on the real-world implementation of the models. The problems faced in model synthesis typically involve specifying a model so that it can guarantee various prescribed or desired characteristics, i.e. a prescribed schema of problems and their solutions. Once this has been done, the model can be used to enable the creation of something real, for example the construction of a prototype. This is illustrated by the example of a diesel engine's functional specification document. It is necessary to "synthesise" a model incorporating the complete set of design documents for the engine. This is where it is possible to employ the range of theoretical ideas provided by the technological sciences about objects and processes that might be created. First of all, it is necessary to translate the prescribed schema of problems and their desired solutions from the "modelling language" into the language of technological ideas or design. In the example above, the issues addressed within the functional specification document and the different engine concepts are translated into issues that relate to a Carnot process. It is then necessary to find a combination of ideas that can accurately produce this specific schema whilst also allowing for features that make it suitable for the model's subsequent implementation. This model synthesis scenario is typical of the tasks that engineers are confronted with. The transformation of concepts from the modelled world into those of the technological sciences and back again should not be viewed as an end in itself. In fact, these transformations between the worlds of theory and practice are undertaken for very practical reasons. The technological sciences thus set themselves the challenge of considering design engineering alternatives with very different structural features. This means that for every model an engineering design can be specified that is tailored to the specific problems being addressed. The relevant theory is then also adapted to the issues at hand.

As far as **model analysis** is concerned, the main support that the technological sciences can offer is to catalogue adequately the features of existing artefacts or fully developed ideas for creating objects and to compare them with a relevant theory. This involves the specification of correspondence rules that define the relationship between existing artefacts and ideas about potential artefacts and the models derived from the relevant theory. This typically involves two main types of situation and two different methodologies:

Methodology 1: Let be given a model (e.g. the design documents for a diesel engine or a description of an existing diesel engine) and the associated problems (r.p.m., performance, fuel consumption, etc.). The aim is to find the solutions that the model is capable of delivering for the individual problems (performance features, etc.). A technological science concept that is appropriate to this model (e.g. a "special Carnot process") can make a significant contribution to finding solutions for the relevant problems. This can be a successful approach as long as the concept is accompanied by an effective theory (e.g. technical thermodynamics) from which methods are derived that are superior to the methods belonging to the model (which can only ever come about or be developed for specific situations).

Methodology 2: Let again be given a model (e.g. the design documents for a diesel engine or a description of an existing diesel engine), but in this case let it be accompanied by a number of desired solutions (e.g. diesel engines with specific forced induction or cooling properties). The aim is to find the set of problems (e.g. optimal reliability in desert regions where dust levels are high and fuel quality is poor) that require precisely these solutions. This situation arises when investigating the causes of known effects. Here too, a "special Carnot process" concept belonging to the "special forced induction" model can prove useful.

As far as **model optimisation** is concerned (a process that extends from the original model from the beginning of the design process or design chain right up to the improved model at the end of the process), a variety of possible behaviours already exist based e.g. on simulations and/or alternative potential structures. It is in fact more accurate to talk of "model improvement". The focus here is on the optimal changes that can be made to the model and the theories that can be mapped to the model's attributes. The nature of the solution principle plays an important role in this context, as does the target function derived from the artefact's environment and how this is formulated.

Following systems theory the technological sciences differentiate appropriately between behaviour (dynamics) and structure. In this context, the theory that addresses different forms of behaviour is known as behaviour theory. It encompasses input-output behaviour, stability behaviour and learning behaviour. Structure theory, meanwhile, seeks to describe the structure of an existing or imagined technological entity. It investigates the individual sub-structures and describes their relationship to the system as a whole. Where several structures exist, it is of interest to identify which combinations of a set of existing structures can lead to the successful creation of a new device or system. Switching circuit theory is one example of a theory that addresses this or similar types of problem. This theory is of fundamental importance for the composition of complex constructs from elementary components. When using these theories, engineers need to check whether the predictions that they make about the models of their artefacts and thus about the artefacts themselves are in fact accurate. They also need to be able to explain these predictions. This theoretical framework is the contribution that the technological sciences make to the current state of knowledge about technology. It serves as a yardstick for engineers and provides a basis for their actions. As long as engineers ensure that their models and model-based predictions stay within this framework – i.e. if they can functionally map their models to both the theories and to existing artefacts –then they will have complied with their duty of care (see Chapter 6). It is therefore crucial that the set of theories in the technological sciences should not contain any invalidated hypotheses, unproven assumptions or singular observations that cannot be replicated. The set of theories should be accurate to the best of our knowledge and belief and should describe knowledge that is widely accepted.

The technological sciences have a duty to ensure that this knowledge about appropriate procedures and facts is as reliable as possible. This responsibility does not only apply to the process of making an assumption about a function, developing a concept, designing a technological entity, making a model and finally building an artefact. It also applies more generally to the use of all technological products both in industry and in our everyday lives, right up to the end of the product's life cycle, i.e. including disposal and recycling. In order for this to be possible, it is tacitly assumed that the rules and conditions of use stipulated by the relevant theory have been followed both in the model and in real life. The technological sciences also have a duty to continuously try and improve our knowledge and to provide the necessary resources for establishing design priorities.

The particular responsibilities of the technological sciences and their different fields and individual disciplines include

- developing theoretical concepts for objects that could potentially be created and systematically describing their behaviour,
- developing potential structures and structural forms and systematically comparing them with each other,
- testing conceptual ideas, structures and theories in a targeted and substantiated manner using both models and real-world implementations,
- demonstrating how these concepts can be synthesised to create processes and be employed in a targeted and efficient manner for different classes of applications, and
- explaining to the public why particular choices have been made and making them aware of the limits on what the technological sciences can know.

It follows directly from the above that the technological sciences have a particular duty to ensure a theoretical form of "correctness" and a practical form of "facticity". This form is determined by checking whether it is compatible with an accepted theory about a particular topic, or can be derived from or explained by this theory. If so, then the result is valid within the framework of this theory. In the technological sciences, this equates, metaphorically speaking, to the "state of the art". However, this does not mean that only fully validated knowledge can be used, since if this were the case it is unlikely that there would be possible any overall progress or individual advances at all in the technological sciences. It is therefore important to ensure that a hypothesis is marked as being a hypothesis and a conjecture about a possible function is marked as being no more than an assumption, i.e. as knowledge that has only been partly validated. It is likewise important always to state the limits within which a theory is valid. Furthermore, a careful distinction must be drawn between natural facts (natural properties, the laws of nature) and institutional facts (the economic, political, legal and social frameworks). Existing knowledge must not be denied or withheld, and experimental results and experimental preconditions should obviously not be faked or falsified.

5.2 PREDICTIONS – METHODOLOGIES – LIMITATIONS

The beginning of the design of artefacts and thus of appropriate models (see above) can be suggested by knowledge gained from casual observations of regularities. In most cases, however, they are inspired by knowledge of scientific hypotheses and conjectures about possible functionalities that are derived from the laws of nature. Predictions made in experiments correspond to conjectures about functionality in tests (see Chapter 4.1). In the field of design, predictions principally are forecasts of effectiveness and, if at all possible, efficiency of a function that is implemented with technology. They describe the execution of a process that is possible in nature under the prescribed boundary conditions and whose outcome is intended (i.e. fulfilment of a function). Even though they are always very much based on simplified models, predictions are nonetheless necessary and indeed key to the implementation of technological functions.

Chapter 4.3 explains the distinction between experiments and tests. In a test, a "B per A" rule is deemed to be effective if the desired function is achieved, as long as the initial and boundary conditions have been properly set, including the sequence of actions to be performed on the artefact – i.e. its operation. In the technological sciences, it is thus not enough simply to be able to predict how a process will unfold. It is also necessary for the process to be repeatable. If a process that performs a technological function can be replicated in a wide range of different circumstances, it can be deemed to function reliably. Inversely a test that fails does not necessarily show that a rule is ineffective. The same rule may prove to be perfectly effective under different conditions or for different purposes. It follows from this that the empirical approach within the realm of technological knowledge is structured differently than in the natural sciences. In the technological sciences, conjectures about possible functionality should therefore be regarded as qualitative predictions that are complemented by quantitative forecasts.

In general, science has two ways of making quantitative predictions. The first approach is geared towards optimising structures. It involves referring to the laws that govern the process to be predicted, inserting into the solution manifold - for the specified initial and boundary conditions - the future points in time at which one wishes the state to be known, and performing the relevant calculations. The second process, which is focused on behaviour, involves observing the process over a long period of time, describing it with a time series and matching this time series to an appropriate function.

6 RESPONSIBILITY

Like the other action oriented sciences, the technological sciences are closely connected to the world of practice. This means that they are confronted with specific problems in terms of evaluation and responsibility. It is thus just as inaccurate to suggest that science is ethically neutral because it only deals in theories as it is to claim that the responsibility for technological artefacts once they are functional rests solely with their users and not with the engineers who developed them. It is therefore clear that the technological sciences need to address the issue of responsibility.

The first fundamental problem that arises in connection with scientific responsibility is how to classify the multiple relationships involved: who is responsible for what, why are they responsible, who are they responsible to, how long should their responsibility last and which values and criteria is it based on? These questions are accompanied by the more practical issue of which sanctions can be taken? By combining these categories, it is possible to come up with different definitions of the subject and object of the responsibility as well as its grounds, timescale and who the subject of the responsibility is answerable to. It will become apparent that the definition of the subject, object and who the subject is answerable to will differ from one case to another and be extremely diverse. This discussion has nonetheless proven to be valuable, since it has demonstrated that the definition of responsibility needs to be specified separately for every situation and problem. There is a clear difference between the type of responsibility that involves liability issues and criminal penalties – for example where a middle-ranking executive at a manufacturing company continues to be held responsible for the recall of a faulty product in the automotive industry even several years after the event – and the responsibility of the technological sciences towards society as a whole for the consequences of technology or the education of young scientists.

6.1 RESPONSIBILITY IN THE TECHNOLOGICAL SCIENCES

The first question that needs to be answered is whether responsibility in science resides with individuals or whether it is collective in nature, residing with groups of decision makers such as boards of directors, teams, committees or even government cabinets and parliaments. The issue of whether this type of collective responsibility should exist is much debated in the field of ethics. The answer is usually pragmatically determined by the sanctions that can effectively be taken against groups of people over and above those that can be taken against individuals, such as criminal sentences, civil law measures, exclusion from the scientific community, loss of prestige, dismissal from one's job, etc. The practice of collective authorship which has now become the norm in the scientific community also involves each individual author assuming responsibility for the publication in question.

There is also no clear answer to the question, of whom scientists should be answerable to. This issue cannot be separated from the question of what a scientist or group of scientists should be or feel responsible for. While people cannot be expected to take responsibility for the outcomes of their scientific investigations per se, they are responsible for the quality of these scientific results, i.e. for ensuring that their work complies with the relevant scientific standards. There is much debate about whether a scientist should be responsible for the products that have been or will be made based on a particular discovery following a process of technological development. Controversy also surrounds the question of whether scientists can be held responsible for the consequences of using these products. While some physicists have recognised their responsibility for the military uses of nuclear power, others have strenuously denied that they are responsible in any shape or form. The debate on this particular topic also demonstrates how attempts to answer this question are very dependent on the role of scientists and engineers and how they themselves understand this role. Scientists involved in basic research will probably be reluctant to take responsibility for subsequent technological developments. Meanwhile, technological scientists, design engineers and industrial engineers may well feel responsible for the correct functioning of a technology, but will not normally accept that they are also responsible for the decision as to whether or not the technology is deployed.

Returning to the question of whom scientists should be answerable to, scientists engaged in basic research might tend to feel a responsibility towards the scientific community (i.e. science as an institution) for the quality of the scientific work that they produce. This is why they observe the scientific community's rules, standards and established verification procedures (e.g. the review procedures for publications). The scientific community, meanwhile, has evolved subtle ways of imposing sanctions, ranging from rejection of a paper to exclusion from the scientific community. Engineers, on the other hand, will tend to feel responsible towards the people who have commissioned the project they are working on, whilst craftsmen and technicians will feel directly responsible towards their customers, who are quite clearly in a position to impose sanctions on them.

Ultimately, both basic researchers and engineers have a responsibility towards society and indeed towards the global community as far as issues such as human rights are concerned. It is thus in the interests of technological scientists to be conscious of their personal responsibility and engage in the public debate as a matter of duty.

The concept of responsibility presupposes the ability to judge whether or not a responsibility has been met. Since even the question of what scientists are responsible for is hotly debated, it is necessary to draw a distinction in this context. Is it individual technological scientists, their teams, or their institutions who are responsible for determining what they research, develop and design and how and why they do so? Can individuals be held responsible for the way that research and development is carried out? And are they responsible for the way that the things they research and create are used or for the direct and indirect consequences of their research and its application? Is the prevention of misuse and failure an intrinsic part of the design process? Whilst these are undoubtedly controversial questions, it cannot be disputed that a person can only be held responsible for what they are capable of doing – responsibility is ultimately a question of what someone has done or neglected to do.

Irrespective of whether or not some of these questions should be subject to a moral judgement, a set of criteria are still needed on which judgements can be based. There is a school of thought in the philosophical discipline of ethics which believes that ethical standards and principles (such as Kant's categorical imperative or the golden rule) are not enough on their own to judge concrete actions or decisions. This is because these principles only provide processes for testing whether certain criteria can be generalised. In order to establish the criteria themselves, it is therefore also necessary to have values that can be used to derive normative statements from the principles, for example legal regulations, statutory requirements and bans, or moral judgements.

Every cultural and communication community develops a different value system based on its needs and view of the world. It is therefore necessary to avoid "deriving" generalisations about values from theories of evolution, the human mind, society, history and politics.

The formerly standard way of dividing science into the idealised categories of basic research (pure science), applied science and technology (i.e. the field of application) produced a false division with regard to the relevant "responsibilities". The basic researchers shifted the responsibility onto those who applied their findings, whilst the applied scientists shifted it onto the decision makers. Today, the problem is framed somewhat differently. Whilst many people question whether it is possible to attribute responsibility to science as a whole, it is certainly felt that responsibility can be attributed to individual scientists and the scientific institutions that they work at, with and for (see Chapter 6.2).

The current ethical debate distinguishes between role responsibility and moral responsibility. Role responsibility concerns functionaries or professionals performing a job either for themselves or for a third party (e.g. engineers, surveyors, doctors, lawyers, board members). In this instance, the responsibility relates to the job that they are performing and they are generally answerable to the person who commissioned the job or the institution for which they are working. Moral responsibility, on the other hand, is responsible behaviour as a human being that is not connected to any particular job. It relates instead to everything we do and judges our actions based on moral criteria that are as widely applicable as possible. These two types of responsibility can sometimes come into conflict with each other. For example, an individual's loyalty to a particular company might be at odds with their environmental convictions, whilst economic imperatives can be incompatible with political beliefs or safety considerations. Conflicts can also arise if different values are used to judge the same action. It is important to understand this in order to avoid moral absolutism and to properly comprehend these conflicts.

Technological scientists make validated statements about the subject of their knowledge within a given framework. Rather than doing this in an abstract space, they generally do it because it is their job or obligation, even if this job conflicts with their own personal interests. Their employer or the institution on behalf of which the job is being performed provide the financial and material resources for their scientific work and therefore have a right to expect that they will adopt a systematic approach and make efficient use of the resources made available to them. However, sometimes new insights can in fact be better facilitated by an unsystematic approach, although this does not apply to their validation.

It follows from the above that a scientist's responsibility as a scientist – and thus also as a technological scientist –in no way exempts them from their moral responsibility as a human being. They still have to decide on their own values, principles and standards and no one else can make these choices for them. Nonetheless, the criteria that define their role responsibility as technological scientists and engineers are far more concrete, even extending to liability issues. It is therefore necessary to provide guidance on these responsibilities in the technological sciences. One could even go so far as to insist that, given the need for prospective technology evaluation, values should in fact form an integral part of technological science theory and analysis, since technological knowledge can never be completely free of values.

A number of specific moral problems that are less important in other sciences occur at the point where models are converted into (engineering) designs, when numerous alternative designs are still possible. The more dangerous an artefact is if not used for its intended purpose, the more serious the question of liability. This is illustrated by the existence of terms such as "high-risk technology". It is less common for research findings in the humanities to be directly linked to a risk of harmful consequences, except insofar as they provide the seed for harmful ideologies and philosophies. Although it is impossible to foresee every way in which a technology may be misused or used for purposes other than those for which it was intended, the responsibility for a technology's consequences can sometimes be traced back to its design. In this situation, the responsibility for the job specification and the responsibility for its execution do not always reside with the same person. This scenario involves a particular responsibility to provide comprehensive information, potentially leading to loyalty conflicts vis-à-vis the person who commissioned the job. Contract research can also put technological scientists in a difficult position if the contract research pursues ends that are at odds with the researcher's personal convictions. In this age of global *simultaneous engineering*, a further problem arises from the fact that engineering decisions are now taken by teams or committees rather than by individuals. However, the traditional concept of responsibility is applicable for such decision rather to an individual than a group of persons.

Limited resources inevitably pose the question of how resources should be allocated to different types of knowledge and design work. If a particular company has funded a research project right from the outset, it has no incentive to share the knowledge thus acquired with any third parties who were not involved in the project. Meanwhile, if the work is publicly funded, e.g. through an organisation such as the German Research Foundation (DFG), the researcher is obliged to transfer and disclose the results to the public. Conflicts can arise when mixed funding models are used in the field of industrial research, and these conflicts can sometimes also have legal implications.

Limited resources also mean limited investment in safety considerations issues at the design stage. Can the person who decided to cut e.g. the preventive maintenance budget for financial reasons subsequently be held responsible for any harm that occurs as a result? Even if we believe that this should in fact be the case, the legal implications of this responsibility have yet to be fully clarified.

6.2 RESPONSIBILITY IN TECHNOLOGY

There are a wide range of ideas about the responsibilities of engineers that have led to the formulation of guidelines and codes of conduct. Common to all of them is the fact that while they address the particularly creative nature of engineers' decisions and actions, they link these to specific aspects of each individual discipline's own understanding of itself. Whilst it is perfectly legitimate to do so, this does make it difficult to extrapolate more general conclusions at the relatively unspecific level of the technological sciences as a whole. It is thus not surprising that virtually every discipline and branch has developed and published its own separate code of conduct.

This is illustrated by the Ethical Principles of the Engineering Profession developed by the Association of German Engineers (VDI), which contain a very broad definition of what engineers are responsible for and who they are answerable to. For example, they state that in addition to being responsible for conscientiously performing the specific duties accorded to them because of their particular skills and expertise, engineers are also responsible for the consequences of their professional work. In situations where several people are working on the same thing, the responsibility is shared by all of them. What this means is that they are answerable for their actions not only to their fellow professionals but also to public institutions, employers, customers and the people who use their technology. The guidelines also refer to a duty to deliver useful technological innovations and solutions. Engineers meet these responsibilities by ensuring the quality, reliability, safety and technically correct documentation of their technological products and processes. The code of conduct also states that technology should be engineered to enable independent action in both the present and the future. Whilst this does not completely rule out potential conflicts, it can help to defuse them through greater transparency.

Another problem is that most of the values that are shared by the vast majority of cultures also conflict with each other in certain respects. Values describe what we should strive to achieve and the underlying understanding of what is regarded as valuable or admirable. In terms of making value judgements about technology, the VDI's proposed list of values constitutes a brave first attempt at drafting a concrete, albeit necessarily incomplete, set of material ethical values. The value categories that can be used to make judgements about technological products and the direct and indirect consequences of using them are as follows:

correct functioning, cost-effectiveness, prosperity, safety, health, environmental quality, personal development and societal quality. It is immediately apparent that there are both underlying conflicts between these categories and conflicts in terms of the end-means relationships. Rather than simply establishing prescribed sets of priorities, many of these conflicts can only be solved by discussing them with the stakeholders in each specific situation. Prescribed priorities state that in the event of a conflict, some values should be treated as more important than others. The question is whether these prescribed priorities – e.g. safety over cost-effectiveness or personal development vs. societal quality – should apply immutably every time that a judgement is made, or whether they can in fact change over the course of time, as the body of knowledge in the technological sciences grows. It is thus indispensable for the technological sciences to engage in a structured public debate about what we want to achieve through technology and which types of technology we want.

It is important that this debate should weigh different values up against each other, for example utility against harm. In this particular instance, safety is one of the most important factors. The term "safety" is used here to encompass everything from the structural stability of buildings to the functional safety of devices and the reliable prediction of the odds that the resources employed in a project will deliver the desired benefits against their potential to cause harm. It even includes the prevention of operating errors and misuse. Safety and serviceability are particularly contingent on random events and cannot therefore be expressed as deterministic values. Their "average value" (as a heuristic concept) is determined by the volume of resources employed by society for the purpose in question, the quality of the engineer's work, the way that the technology is operated in practice (e.g. operating errors or misuse) and external events such as earthquakes. Consequently, the moral and legal responsibility for the residual risk that is always implicit in any engineering project should be shared fairly between the engineers and society. Ultimately, it is not only the users of a technology or the people affected by it who are subject to residual risk. Engineers, too, are faced with residual risk in terms of their responsibility and legal liability for any harm caused as a result of technologies that they have planned, built, installed, operated or disposed of.

Legal liability can to some extent be regarded as a concrete, material form of responsibility. Engineers as individuals are responsible, and therefore liable, within a legal framework to both their customers and society as a whole. Nevertheless, the concrete nature of this liability changes as the responsible person becomes more remote from the concrete technological design For example, someone may be guilty of dishonourable scientific conduct. Then he can be held to account by punishments such as exclusion from the scientific community. Nevertheless, in this case he is no yet subject to legal liability.

Technological scientists working as engineers in the applied areas of their discipline can use these ethical principles as a basic guideline. Their key message is that our universal moral responsibility as individuals (what we feel responsible for as human beings) should take precedence over our role responsibility (as engineers, developers or managers). As far as their responsibility for technology is concerned, engineers must ensure the quality, reliability and safety of their technological products. They are also considered to be jointly responsible for ensuring that people are properly informed about how to use technological products, so that they are used correctly and avoidable operating errors are prevented. The guidelines place particular emphasis on engineers' strategic responsibility for taking account of undesirable developments and the potential for deliberate misuse, and recommend that they ensure the conditions for responsible behaviour when designing a piece of technology, i.e. that they enable the user to operate the technology in a responsible manner.

Particularly those technological scientists working in action oriented disciplines and design are thus reliant on their professional organisations providing them with ethical and legal advice. However, their high level of technical expertise also means that they have a duty to engage in the public debate about responsibility in technology and rather than restricting themselves to accounting for its consensually agreed outputs, they should also reflect the debate's concerns, provisional findings and sensitive topics in their work as technological scientists. Moreover, in case of doubt they should themselves draw attention to the fact that there is a need to clarify the ethical situation pertaining to an existing or possible future technology.

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