Chapter 8

Engineering Science as a "Discipline of the Particular"? Types of Generalization in Engineering Sciences

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Abstract Literature suggests that in engineering sciences the possibilities to generalize knowledge are more limited than in natural sciences. This is related to the action-oriented nature of engineering sciences and to the role of values. I will discuss the contributions of abstraction and idealization to generalization and then describe four case studies in engineering sciences to illustrate that different types of generalization can be distinguished. I will then analyze the nature of these types of generalization.

8.1 Sciences of the Particular: A Contradiction in Terms?

In a 1975 article on medical fallibility, Samuel Gorowitz and Alasdair MacIntyre argued that the use of medical sciences can easily lead to failures when the knowledge generated by these sciences is of too high a level of generality. Therefore they made a plea for medical sciences to be "sciences of the particular". They were well aware that this goes against a longstanding bias, going back as far as the time of Plato and Aristotle, towards sciences as being focused on generalization. The natural sciences with their highly generalized knowledge have served as the model for all sciences for a long time. But as Gorowitz and MacIntyre showed, general laws in medical sciences do not necessarily give an accurate description of an individual patient. They claimed that knowledge of particulars should be accepted as truly scientific knowledge, no less than generalized knowledge. Clearly, the need to be modest in generalizing knowledge in medical sciences is related to the nature of these sciences: application to practical situations is the main aim for developing such knowledge. This raises the question if the same concern about generalization also applies to other sciences that are developed primarily for practical purposes. Engineering sciences are an example of such sciences. These sciences

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are mentioned by Ladislav Tondl in an article on the limitations to generalization in certain sciences, among which he reckons what he calls "sciences of artifacts" (Tondl 1998). It is evident that engineering sciences to a large extent develop knowledge that is somehow related to (technical) artifacts. Rather than using the term "application-orientation", he wrote about "action-orientation". Another author that used the term "science of the particular" is John Meurig Thomas (cited by Ball 2006). He used the term for industrial chemistry, again a science that can be regarded to be an engineering science.

Gorowitz's and MacIntyre's idea of a "science of particulars" is supported by the distinction, introduced by Windelband and later by Rickert, between nomothetic and ideographic sciences. These authors showed that there are sciences that differ in nature from natural sciences, and yet are considered to be genuine sciences. Historical sciences are an example of that. Historians do not necessarily seek "general laws" in history. Rather, they aim at providing an accurate and observer-independent description of individual persons or occurrences. Windelband and Rickert, no doubt, were too naïve when they equated the distinction between nomothetic versus ideographic sciences and the distinction between natural versus cultural and human sciences. But the idea of some sciences aiming at general laws and others at describing particulars has been widely accepted now. This raises a question concerning the nature of engineering sciences: are they primarily "sciences of the general" like the natural sciences to which they are so closely related, or do they differ from natural sciences in their generalization claims? If they are different and more aimed at knowledge of particulars than natural sciences are, then, of course, they still must have some tendency towards generalization in order to be a science. How does that work for engineering sciences?

Before I move on and focus entirely on engineering sciences, I want to point out that the term "science of the particulars" was also used by James Ogilvy (1976) to characterize the science of aesthetics. He claimed that this was related to the values that feature in aesthetics. Values differ between people and this sets limits to the possibilities to generalize knowledge claims in aesthetics. This provides a second motive for investigating if the same limitations appear in engineering sciences, apart from the action-oriented nature of certain sciences, as values also feature strongly in engineering sciences. In Gregory Cooper's article on the limited generalizability of knowledge of ecology both aspects come together (Cooper 1998): ecology is a science that primarily is developed to be applied in practice, and values feature strongly in it.

This chapter will not yet answer the question as to which are the boundaries for generalizing in engineering sciences. What I will do here as a first step towards answering that question is to investigate how generalizations are made in engineering sciences. What types of generalization can be distinguished? Do they match with typologies for generalization in sciences that others have developed? These are the questions that will be the focus for this chapter.

8.2 Generalization, Abstraction and Idealization

How is knowledge generalized in sciences? There are at least two ways that can lead to generalizations. In the first place there is abstraction. I will use the term abstraction for abstaining from certain aspects of reality in order to get a deeper understanding of the remaining aspect(s) (from the Latin abstrahere, which means something like: peeling of). The physicist when observing a cat falling from a roof, abstains from describing the fact that the cat is a living object, for whom the owner maybe paid money, and whom (s)he dearly loves, to describe only the motion of the falling cat in the language of mathematics. By doing that, the scientist can generalize the outcomes of studying the cat's motion to the motion of any other object, irrespective whether it lives or not, whether or not it is natural or artificial, whether or not it costed money, and so on. Likewise the engineering scientist leaves out certain aspects of the artifacts (s)he studies in order to be able to generalize from one particular artifact to a broader set of artifacts. But usually the focus of the engineering scientist is less narrow than that of a natural scientist. Although a description of the physics of the artifact is important for the engineering scientist, dealing with that only would mean reducing engineering to science, and as both history and philosophy of technology have shown is an inappropriate reduction. In engineering sciences several different aspects of reality must be kept in focus to make the outcome useful for the designer or maker of artifacts. To reduce the artifact to "just a matter of nuts and bolts" or "just a matter of money" would not result in a valuable understanding of the artifact. Still, a certain degree of abstraction does take place in the engineering sciences otherwise engineering research would be as complex as reality itself.

A second "mechanism" that can lead to generalization is idealization. According to Mark Shephard (1990) it is a "fundamental part" of the design process. But according to Sven Ove Hansson (2007) in engineering science the possibilities for idealization are more limited than in natural sciences. This supports my earlier claim that literature suggests that generalization in engineering sciences is different from that in natural sciences. I will use the term in the following way: by replacing a complicated detail of reality by a simplified version of that detail (e.g. by presenting a rough surface as if it were smooth) possibilities for generalizing knowledge claims emerge. By developing knowledge about a completely frictionless surface, the physicist can make claims that hold for a variety of more or less smooth surfaces, at least as an approximation. The difference with abstraction is that the outcome is not knowledge that is limited (because aspects of reality have been left out) but inaccurate (because an approximation has been made). Abstraction does not change the description of reality but only limits it; idealization describes reality is a (slightly) different way than it is. Here, too, engineering sciences meet more limitations than natural sciences. If the knowledge generated by engineering sciences is to be applied to real artifacts, it can not be too much "distorted" by idealization to be useable. Walther Vincenti has already pointed out that the use of knowledge from natural sciences in engineering requires a transformation because of the gap between the idealized description of reality in the natural science theory and the actual artifact (Vincenti 1990).

It would seem that these two “mechanisms” for generalization lead to the two types of generalization as distinguished by Bailer-Jones (2003). She wrote about construct idealization and causal idealization. In construct idealization, the conceptual representation is only simplified, so that there is no necessary loss of truthfulness. It is just that only part of the truth is told. In causal idealization, the phenomenon representation is simplified, such that the resulting representation (model) may not be true for the original phenomenon. Generalization by abstraction is of Bailer-Jones’ construct idealization type, because it only selects part of the aspects through which an artifact can be studied. Generalization by idealization (in my terms) is of Bailer-Jones’ causal idealization type, because we make an “as if” representation of reality. Later I will show that for engineering sciences it can be useful to define generalization types not based on either abstraction or idealization, like in Bailer-Jones’ typology, but having types that allow for combinations of the abstraction and idealization “mechanisms”.

8.3 Taking an Empirical Turn

Although the considerations above give us a first impression of what limits the generalizability of knowledge and theories in engineering sciences, the picture is still rather vague. Paraphrasing on Vincenti’s example of “stable but not too stable” as the pilots’ vague way of expressing their needs to the designers of aircraft, we could say that knowledge in engineering sciences should be “general, but not too general”. That, of course, is not satisfactory and we would like to gain further insight into the different ways in which knowledge in engineering sciences can be generalized and what limits this. For that purpose I will use a case study approach. This fits well with what Kroes and Meijers (2000) have called the “empirical turn” in the philosophy of technology. This does not mean to turn philosophy into an empirical science, but to make it an empirically informed science. Philosophy of technology, in particular analytical philosophy of technology, then becomes systematic reflection on the practice of technology and engineering.

In my case, I will use case studies from the history of the Philips Natuurkundig Laboratorium (in English: Philips Physics Laboratory). Since its initiation in 1914 this has been the main research facility in the Philips Electronics company, a multinational company that produces a great variety of artifacts, such as consumer electronics, household equipment and medical equipment. In my book on the history of this lab, I have shown that a corporate industrial research laboratory can be seen as a contributor to engineering sciences, because the knowledge generated in it is often published in academic journals (De Vries 2005). Therefore examples from work done in the Philips Natuurkundig Laboratorium can be used to illustrate how knowledge in engineering sciences can be developed. The researchers in the lab were called “scientists” by themselves as well as by others. Their claim was that the knowledge they developed was truly scientific knowledge. In order to stimulate publication of this knowledge in the scientific world, the lab had it’s own research journal called the Philips Technical Review. I will use material from this journal to describe four cases of the development of engineering science knowledge. If we take engineering sciences to be those sciences that develop knowledge in the context of technological problems and challenges, then the knowledge developed in the Philips Natuurkundig Laboratorium can certainly be called engineering science knowledge. The research that was conducted was always in some way or other related to the company’s main activity, namely the development and improvement of new artifacts, systems and processes. Besides that, a substantial percentage of the researchers had been educated in engineering colleges or universities of technology, and therefore were engineering scientists by training.

8.4 Four Case Studies

Case 1: Microwave Oven Characteristics

My first case study is based on an article by W. Schmidt, titled “The heating of food in a microwave oven”. It was published in 1960. The author worked at the development laboratory at the Valvo Ltd. radio tube factory in Hamburg, Germany. The article deals with a microwave device that had already been developed and was produced for industrial purposes (heating wood or textile products or the welding of plastics). Several type numbers are mentioned in the article, which indicates that the microwave device had already been developed in a number of variants. The author focuses on what in that time was still a relatively new application, namely the heating of food. For restaurants this seemed to be a useful application because of the speed with which the food was heated. In conventional ways of preparing food (cooking, baking) one can only heat the exterior of the food and the inside gets warm through conduction. By using electromagnetic waves of around 2400 MHz (which is in the microwave range) for dielectric heating the inside of the food was heated directly. As a result the heating took only one fourth to one eighth of the time needed for conventional heating. This would solve both the problem of the current lack of personnel in restaurants and the problem of serving great quantities of warm food (for many customers) in a short time. The author expresses the expectation that in the end the microwave oven might also be used in households, which would particularly be convenient for housewives who also had a job.

The article presents the outcomes of measurements for microwave types 7091 and 7292. These types are identical as far as the produced electromagnetic waves that are produced; the only difference between the two types is that 7091 is air-cooled and 7292 is water-cooled. The measurements concern the way the frequency and the power of the generated waves relate to the load impedance of the oven when the power generated in the resonance cavity of the microwave is taken over by a coaxial line. This relationship is presented in what is called the Rieke diagram, a polar diagram in which the curves each represent a value of the wave frequency and the combination of radius vector and azimuth represent the combination of load impedance and the generated power. Although the article does not mention this explicitly we must assume that the measurements have been done with a limited number of tokens of the two microwave types. Yet the Rieke diagram is presented for the two types in general, that is, for all tokens of these types. Early in the article the author emphasizes the need for an accurate similarity of all tokens. The microwaves must be easily replaceable because in many cases the replacement will be done by non-experts (e.g., restaurant personnel) so that tuning because of differences between the old and the new device must not be part of the act of replacement. The author's assumption is that indeed all tokens of the types are identical so that the Rieke diagram is valid for all tokens. This is a first type of generalization: conclusions based on measurements done on a limited number of tokens are assumed to be valid for all tokens of the type.

Case 2: Transmitter Pentodes

The second case study deals with transmitter pentodes. In 1937 an article on this topic by J.P. Heyboer was published in the Philips Technical Review. Heyboer was a researcher at the Philips Natuurkundig Laboratorium. The pentode was one of the most important Philips inventions of that period, made by B.D.H. Tellegen in 1926. In the triode there are three main parts for different functions: the cathode is for producing electrons, the anode is for capturing them, and there is a grid (called the control grid) for regulating the electron flow from cathode to anode. The triode's functioning was hampered by the capacity between anode and grid, which could easily result in an undesired auto-oscillation of the current in the tube. To fix this problem, in the tetrode another grid (called screen grid) was added to the design, between anode and grid, and this functioned as an electrostatic insulation. The tetrode, though, had a new problem: now electrons hitting the anode caused secondary emission of new electrons at the anode, which electrons caused other electrons coming from the control grid to be turned back. Tellegen solved this new problem by putting another additional grid (called suppressor grid) between the insulating grid and the anode. When this grid had a negative potential (approximately the same as the cathode) the electrons approaching the anode were no longer hampered by secondary emission at the anode. But this additional grid also could be used as an additional control grid. By positioning the bars in the additional grid in the electrical "shadow" of the bars in the original control grid, the secondary emission was reduced (so not only the effect of secondary emission is dealt with, but also the emission itself). Furthermore, the variation in capacity between the cathode and the control grid became very small, which suppressed practically every frequency shift when the tube was used in a wave generator circuit.

The article contains some measurements done on the Philips PE 05/15 pentode. A graph of the anode current versus the anode voltage for different voltages of the control grid and for a specified voltage of the screen grid and the suppressor grid is presented and used to explain the advantages of the pentode over the tetrode: for a long range of anode voltages the anode current is constant (contrary to tetrodes, where a fluctuation can be seen), so that an alternating current is amplified without distortions, even when the highest value of the alternating voltage is almost as high as the constant anode voltage. The type number of the tube (PE 05/15) is dropped in all conclusions, so that we must assume that the author claims that they hold for all pentodes and not just for the type that was used for the measurements. At the end of the article the author presents data concerning a different pentode type (the PC 1,5/100) and still uses the conclusions drawn from the graph that was made for the PE 05/15. Then he lists a whole range of type numbers (PC 1/50, PE 1/80, PC 3/100 and PA 12/15). Evidently, he suggests that the conclusions drawn for the PE 05/15 hold for those as well. Here we see a second type of generalization: conclusions based on measurements done on one type (of pentode) are claimed to be valid for all types of a class (of the pentodes). This can be seen as an extension of the first type of generalization.

Case 3: High-Speed Sparking Machinery Equipment

In 1982, J.L.C. Wijers, one of the researchers at the Philips Natuurkundig Laboratorium, published an article in the Philips Technical Review on applications of high-speed sparking machinery equipment. This equipment had already been developed in the late 1960s at the Philips Natuurkundig Laboratorium and since then different applications had been studied. The aim of the article is stated in the abstract: to discuss the “promise of universal applicability” of the equipment. In high-speed sparking machinery material particles on a workpiece are removed by using the spark discharge that occurs when a high-voltage electrode is moved over a conducting material. The heat of the spark causes the material to erode and the eroded material is removed with an isolating fluid. “High-speed” means that per minute some square millimeters of the material surface are sparked away. The expectation was that this type of machining would be particularly suitable for making cavities inside a workpiece and for situations where precise right corners were needed. An advantage of using the sparking technique is that there is no contact between the equipment and the workpiece and as a consequence no mechanical tensions in the material occur during the treatment.

In the article, measurements are presented concerning seven different combinations of workpiece and electrode material. All measurements were done with one machine. The results show that for the combinations of diamond-tungsten/copper, steel-steel, steel-tungsten/copper, hardened tool steel-tungsten, hardened tool steel-tungsten/copper and hardened tool steel-hardened tool steel erosion speeds of 0.59–4.10 square millimeter per minute are realized and surface roughness as low as 0.8–1.5 micrometer. Then the author continues by describing three different applications, each of which profits from these good values: (1) making a miniature bit for thermocompression bonding in integrated circuits, (2) making small spheres of monocrystalline aluminum for materials research and (3) the processing of diamond for tools. In the first two examples the very small dimensions of the tools posed a problem for conventional ways of machining, and the high-speed sparking techniques proved very suitable for such purposes. In the third case precision as needed because the tools were to be used for making optically smooth surfaces and for cutting optical fibers. As the three examples are quite different, the author concludes that the equipment can be used for all sorts of machining processes. This is a third type of generalization: conclusions based on a limited number of examples of a certain treatment are extended to all possible applications of that treatment. Now the generalization does not concern artifact characteristics, but functional characteristics. In this case the function of removing surface particles is the content of the generalization.

Case 4: An Evacuated Tubular Solar Collector with Heat Pipe

The fourth and final case study is an article by Bloem et al. (1982) on an evacuated tubular solar collector with heat pipes. The authors were not from the Philips Natuurkundig Laboratorium, but from two of Philips' Product Divisions, namely Elcoma (Electrical components and materials) and Lighting. The solar collector (with type number VTR141) had been developed by the two Product Divisions by using a technique that had been developed by the Natuurkundig Laboratorium. Solar collectors are used to transform solar energy into heat in the water in the collector. This solar radiation is absorbed by a black panel with water pipes running into it. This panel is isolated from its environment by isolation material under the panel and a covering glass panel on top of it. In a conventional solar collector there is a layer of air between the black panel and the glass cover. This causes loss of heat and therefore the Philips solar panel had the air layer removed (hence the term "evacuated"). A tubular configuration is more suitable for that than a flat configuration. The transfer of heat from the black panel to the water tubes takes place via a heat pipe. The hot black panel makes a fluid in the heat pipe evaporate, and the gas condenses near the water pipe, thereby transferring the condensation energy. The advantage of this is twofold: the heat can not flow back from the water pipes to the black panel, and the system is protected against high water pressures (due to high temperatures). Both advantages are the result of the fact that the heat transfer stops when all fluid in the heat pipe has evaporated.

The production of the solar collector requires a technique for connecting glass and metal as well as a technique for evacuating the space between the black panel and the covering glass plate. These two processes played a major role in the production of Philips' original product, namely light bulbs. To make a light bulb, the glass bulb has to be connected to the metal socket and the air has to be pumped out of the bulb. Although the process had to be adapted to this new application by the Philips factory in Turnhout, Belgium, in effect it was still the same technique. It was not the first time that this technique was transferred to a new application. This transfer played a major role in the diversification of the company's product portfolio in the pre-WWII period. The researchers in the lab then used to say that knowledge of light bulbs is knowledge of "glass and vacuum" and that the same knowledge applied to a variety of tubes, because they also were just a matter of "glass and vacuum”. This enabled the lab to move from light bulbs to X-ray tubes, to radio valves and other amplification tubes (e.g., for telephony). Here we have another type of generalization: knowledge of a physical phenomenon (here: that realizes the desired connection between glass and metal) in one particular artifact (a light bulb) is generalized to all artifacts in which the same physical connection is needed.

8.5 Analysis of the Types of Generalization in the Case Studies

I will now analyze more precisely the nature of the different types of generalization that we encountered in the case studies. Thereby I will make use of the dual nature approach for conceptualizing technical artifacts, as it has been developed at the Delft University of Technology in the Netherlands (in De Vries 2003 I have shown how different types of engineering knowledge can be derived from this approach). In this approach technical artifacts are characterized by their physical nature and their functional nature. The physical nature (or “structure”) is the physical/chemical and structural set-up of the artifact; the functional nature (or “function”) indicates what it is for. The term “two natures” does not refer to a dualistic approach. They are two ways of describing the same artifact, not two parts of the artifact. Using this account of technical artifacts, let us now examine the case studies.

In the first case study, data on one toke of a type are used to make claims about the type. What is assumed in doing that is that all tokens of the type are identical both in their physical nature and in their functional nature. The physical nature, though, is influenced by the production process. Small differences are introduced as a result of tolerances in that process. In the generalized knowledge claim these differences are annihilated. This means that idealization is used for this type of generalization. No abstraction was made in the generalization. One can also say that the conclusions refer to the design of the microwave device, both as far as its function and physical realization are concerned. The design is as it were the model that results from the generalization.

In the second case study, data about one type are used to make claims about other types as well. These types all have the same functional nature (serving as a pentode transmitter tube), but differ in physical nature. To generalize knowledge of one type, it is not assumed that there are no differences between the types in their physical nature (the sort of idealization that was used in the first case study) but the whole physical nature is just left out of the considerations about the kind (pentodes), of which the examined type (PE 05/15) was one type. In other words: in this type of generalization abstraction is applied. In the second case study the various types (e.g., PE 05/15) within the kind (pentodes) still have several physical characteristics in common. In the third case, the differences between the physical natures of the various situations in which the sparking machinery equipment is used differ greatly. As in the second case, these differences are not eliminated in the generalized knowledge claim, but the physical nature is left out and the knowledge claims only refer to the functional nature of the artifacts. There is, though, idealization involved in this type of generalization. It is assumed that there is no malfunctioning resulting from crucial deviations from the design in the physical nature of the artifact. Another appearance of this form of generalization is the use of a systems perspective on the artifact. Such a perspective contains claims about the artifact that only concern functions (and sub-functions), and not the physical realization of the system. Here the system description is the model that results from the generalization.

In the fourth case study, not the physical nature is left out of consideration, but the functional nature is. Knowledge claims about the physical nature ("glass and vacuum") of various tubes are made irrespective of the function of the tube. So here again we have abstraction as the "mechanism" for generalization, but now of a different kind. Here the model that results from the generalization is the physical or mathematical representation of the phenomena that govern the working principles of the artifact. Here, too, we have idealizations, namely the ones that are made in the natural science perspective on the phenomena in question.

8.6 Conclusions

I have shown that literature suggests that generalization is different in engineering sciences than in natural sciences. This makes the topic of generalization in engineering sciences of interest for the philosophy of engineering. By analyzing four case studies, drawn from the history of the Philips Natuurkundig Laboratorium, I have shown that at least three types of generalization in engineering sciences can be distinguished: "artifact-token to artifact-type" generalization, based on the idealization of no production deviations being present in any token; "artifact to function" generalization, in which abstraction takes place (only the functional nature of the artifact is considered), and "artifact to artifact-structure" generalization, in which also abstraction takes place (only the physical nature is kept for study). In the latter two types idealization also takes place. In the second type of generalization any malfunctioning is replaced by proper functioning. In the third type of generalization the idealizations made in natural sciences concerning the phenomena in study are applied. The first type of generalization is of Bailer Jones' "causal idealization" type; the other three are combinations of "concept" and "causal" idealizations in Bailer-Jones' typology.

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