Chapter 22
Substantive and Procedural Contexts of Engineering Design

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Abstract Kroes and Van de Poel (Problematizing the notion of social context of technology. In S. H. Christensen, B. Delahousse, & M. Meganck (Eds.), *Engineering in context* (pp. 61–74). Aarhus: Academica, 2009) maintain that distinguishing between technology and its social (intentional) context is impossible, because social phenomena are definitive (constitutive) for technology. This raises the problem of differentiating between the social processes that are internal (definitive) and those that are external (contextual) to technology. To explore this problem we distinguish instead between the core and the context of design as object and as process, and we apply them to a case study of the design and development of a new technology for sewage water treatment to find out whether these distinctions make sense in real life engineering practice. Despite the *in abstracto* plausibility of this distinction between core and context, our analysis reveals that its application may turn out to be very problematic in actual engineering practices. The same holds for characterizing particular design features as being the result of either internal (technological) or external (social) factors.

Keywords Product of design • Process of design • Social context • Substantive context • Procedural context

Introduction

In their analysis of the notion of social context of technology Peter Kroes and Ibo Van de Poel (2009, p. 71) come to the conclusion that "independently of whether technology is interpreted as a process or a product … it is not possible to draw a

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demarcation line with technology on the one side and its social context on the other. The reason is that the definition of technology as a process or a product involves reference to social phenomena. Social phenomena are conceptually definitive of technology (or, in ontological terms, constitutive of technology)." This means that "it is not possible to treat all social phenomena as belonging to the context of technology, since some social phenomena are definitive or constitutive of technology." Regarding technology as process the authors interpret engineering (design) practices as social practices to show that social phenomena are more than just part of the context of technology, and regarding technology as product they refer to the dual nature of technical artifacts according to which intentional (social) features are constitutive of technical artifacts.

In this chapter we intend to follow up on this analysis of how to distinguish (social) context from technology and to further problematize the distinction between technology and its social context. We focus on the notion of context with regard to engineering design practice. We identify and analyze *in abstracto* two different kinds of contexts, referred to as 'substantive' and 'procedural' contexts. Both contexts appear to be operative in engineering design practice in the sense that they may influence the outcome of engineering design projects (section "Substantive and Procedural Contexts of Design"). To confront these abstract distinctions to real engineering design practice, we describe in detail an actual design and development project (section "Example: GSBR Technology in Nereda Wastewater Treatment"). Finally we examine whether the distinction between substantive and procedural contexts may be applied to this project and so may be of help in classifying factors that influence the outcome of a design and development process as technological (internal) vs. contextual (external) (section "Discussion").

Substantive and Procedural Contexts of Design

Engineering design may be considered as a *process* and as a *product*, viz., that which is developed during this process and finally is presented as its outcome (Kroes and Van de Poel 2009). To delineate these concepts more precisely we follow (Dorst and Overveld 2009). Engineering design as a process is a human activity in which plans are developed to create an artifact that helps the user attain certain of his/her goals and therefore has value for the future users. An engineering design project has many intended, non-intended, known, and unknown outcomes some of which are directly related to (the plans of) the prospective artifact. The (intermediary) artifact related outcomes of an engineering design project we will call the *object of design*. This object of design in its final form consists of at least the following descriptions, viz., a description of the "artifact itself", a description of the interface between this artifact and the outside world, and an outline of how and in which contexts the designer has imagined the artifact should be used. The latter has also been called the artifact's "use plan" (Houkes et al. 2002). The description of the artifact itself should at least cover the *form* of the artifact, its *function* and its *working principle*. Our delineation of the object of design is still very general and allows many kinds of descriptions, which may include blueprints, texts written in natural language, all kinds of mathematical, iconic and structural models, etc. Moreover it does not exclude the object of design to be a process (for instance, a service), in which case the emphasis of the artifact description is on a series of actions, which may or may not include reference to use plans depending on whether or not some actions imply the use of artifacts.[1] Here we do not focus on the distinction between object of design as object or process; whenever in the following we refer to the object of design as an object it is intended as shorthand for object or process. We will concentrate on the distinction between *design as a process* and *design as a product* (which, thus, may be either an object or a process). Note that our general delineation of the object of design does exclude the object of design to be the physically realized artifact itself. Thus the object of design is not the specific building at its unique place as the solution of a design problem. It is the description of the building and of plans for how to build it. So the object of design is an abstract object.

Following the distinction between the object of design and the design process we may distinguish between the *substantive* and the *procedural* contexts of design. Roughly, the first consists of all factors that influence the object of design and the second all factors that influence the process of design. Regarding the former, it is the context that plays a role in determining the design problem that is to be solved. Here we are dealing with contextual factors that have a direct influence on the object of design in the sense that these factors determine what kind of object is to be designed and the list of requirements or specifications it has to satisfy. The procedural context, however, plays a role on the level of the design process and is the set of factors that determine the time frame and resources available for solving a design problem, which, of course, may indirectly influence the object of design. Clearly both contexts 'shape' the object of the design (and thus, a technical artifact that is an embodiment of that design) that is proposed at the end of a design project. Before we turn to a more detailed discussion of the substantive and procedural contexts of engineering design, it is necessary to delve somewhat deeper into the meaning of the notion 'context' that we are using.

Intuitively, the notion of context of something implies that it is possible to distinguish between what belongs to the 'inside' of that thing and what to its 'outside', its environment or context. However, how the distinction between what belongs to the inside and what to the outside is made, may depend heavily upon how the thing under consideration is conceptualized: "The notion of the context of something has a well-defined meaning only from a certain perspective, one which determines what kind of conceptualizations are adequate or useful and which ones not" (Kroes and Van de Poel 2009). With regard to design this means that the distinction between design and its context depends to a large extent on the conceptualization or framing of what design is.[2] For instance, from the point of view of a project manager the

[1] Note that if the object of design is a process (such as a service) then a use plan may be associated with this process.

[2] Note that from this perspective the borderline between objects (or processes) and their contexts is merely a conceptual and not an ontological affair.

context of an engineering design project differs from the context of the 'same project' in the eyes of other stakeholders such as a corporate director, a design manager or a design engineer. For a corporate director the context of the design project may consist mainly of balance sheets, for a project manager a potential new product line may be an important element from its context, for a design manager the patent position of the firm and the search for new patents and for an engineer designer, finally, anything that is not technically relevant for solving the design problem at hand.

Besides differences in framing or viewpoint there are also differences in resolution of a design project and its context (Hales 1993, Chap. 1; Hales and Gooch 2004, pp. 21–23). From the point of view of a manager of an engineering design project that project may be situated primarily within the context of his/her company or within the context of the company's local or national market which in turn may be situated in the context of a global or international market. Which level of resolution is chosen in analyzing a design project and its context (macro- and micro-economical, corporate, project or even personal level) depends, of course, on the specific problem about the design project and its context that one is dealing with.

As have been argued by Bucciarelli (1994), even at a very detailed resolution level, individual design engineers frame their design often very differently, even if they collaborate in one design team. He refers to these framings or viewpoints as "object worlds". After years of cooperative observation in corporate multidisciplinary design teams, Bucciarelli draws the conclusion that the participating engineers see the object of design differently; they live in distinct object worlds. Engineers with different backgrounds such as mechanics, electrotechnics, fluid dynamics, thermodynamics and biotechnology, live in their own object worlds, which are characterized by branch-specific instrumentation, standards, codes, and quantitative instrumental rationality. They tend to concentrate on the "hard stuff" of the design, free of any context in which people and societal values play a role, and are brought up to solve single-answer problems using quantitative methods. Bucciarelli's ethnographical approach shows that today's real-world engineering design practices are characterized by multi-disciplinary teamwork in which many negotiations between individuals from different object worlds are taking place. His ethnographic observations show that there is only partial mutual understanding of the individuals having different conceptions of the object of design. Because there is not one single object of design and because of the negotiations between different design engineers, Bucciarelli concludes that today design is first and foremost a social process. For our purposes the most important lesson to be drawn from Bucciarelli's work is that even at a very fine-grained level of resolution differences in perspective or framing of a design project or object and its context may play a crucial role.

In order to further clarify the role of various contexts in shaping technical artifacts (technology) we will now have a closer look at how contexts may be conceptualized in the case of design as a process and as an object. With regard to the object of design, the distinction between what belongs to its context and what belongs to *engineering design proper* we will take to correspond roughly to the distinction between the kinds of factors and considerations that play a role in fixing the constraints and specifications and those that play a role in fixing the physical structure of the future technical artifact (the design as a blue print for production). More in particular, we assume that design decisions that fix this physical structure on the basis of factors and considerations of a technological or scientific nature are internal to the core of engineering design. Other factors and considerations, that influence design decisions, we take to be part of the context of the object of design. We have been referring to this context as the *substantive context* because it is the context that determines the substance of the design effort, namely what kind of technical artifact is going to be designed.

As far as design as a process is concerned, what belongs to the *design process proper* we take to be primarily those actions that have to be performed in order to bring about an adequate solution to the given design problem in a systematic or methodic way where 'adequate' means that a particular design solution meets the lists of specifications, irrespective of the means and resources available or employed to arrive at this design solution.

These kinds of actions and their order have been studied extensively by design methodologists. They have proposed numerous general flow diagrams that prescribe the various steps that have to be taken in order to solve a design problem in a methodically justified way. We take the *procedural context* of the design process to be the factors that determine the conditions concerning available means, resources and time under which actions can be taken to solve the given design problem. All this is summarized in Table 22.1.

A first comment to be made with regard to Table 22.1 is that the distinctions between object and process and between core and context for engineering design are not crisp or clear cut. This is important to keep in mind. *Prima facie* Table 22.1 suggests that the influence of (social) factors from the procedural and substantive contexts on the object of design are not on a par, since only factors from the substantive contexts define the 'essential' features of the object of design, that is, the features as defined by the list of specifications. Factors from the procedural context appear to have only a contingent influence on the object of design since its influence does not affect the set of features that is definitive for the object of design. Suppose that the same design brief is given to two design teams, that have different resources

Table 22.1 Substantive and procedural contexts of engineering design as product and as process

	Design as a product	Design as a process
Core	Scientific and technological considerations that fix the physical structure of the technical artifact to be (the design as a blue print for production) = 'factors internal to engineering design proper'	The kind of actions (and their order) as prescribed by the flow diagrams of design methodology
Context	The kinds of factors and considerations that play a role in fixing the constraints/ specifications (substantive context)	The factors that determine the means, resources and time available for a design project (procedural context)

available or that have developed different design cultures. Due to these differences in resources or design cultures each design team may come up with a different design solution that satisfies the list of specifications. In that case the influence of factors from the substantive context on the object of design is the same for both cases, but the influence of the procedural factors varies.[3] However, the situation becomes more complicated as soon as procedural factors make it necessary to adapt or revise the list of specifications (for instance, because it turns out not to be possible to meet certain specifications with the available resources). In such situations factors from the procedural context may have a direct influence on the object of design that no longer can be characterized as a contingent influence. In other words, whenever the list of specifications is adapted during the process ("on the fly") for reasons related to constraints put on the design process the above *prima facie* difference in influence of factors from the substantive and procedural context appears to break down, because the distinction and relation between object of design and process of design becomes more complicated than suggested by Table 22.1. As is often remarked, in real life design practices, feed-back loops that end up in revisions of the design specifications during the design process are more the rule than the exception. In so far these feed-back loops find their origin in reasons related to process constraints they undermine the simple picture of the influence of substantive and procedural contextual factors of Table 22.1.

A second comment on Table 22.1 concerns the 'visibility' or 'traceability' of social influences, whether stemming from the substantial or procedural context, on an object of design or technical artifact. Consider the following series of design tasks, ranging from designing a raw material, to designing components, up to designing an end-user product:

1. The design of some steel with properties X, Y, and Z.
2. The design of a valve with that steel for an engine of a certain type
3. The design of an engine for some type of car
4. The design of a car.

It seems that the closer we get to end-user products the easier it is to trace the social influences operative in shaping the technical artifacts and to determine their functional features. When confronted with a specimen of steel with properties X, Y and Z it may be immediately clear that we are dealing with an artifact, something made purposely by humans, since we have never come across steel in nature. But it may be more difficult to trace the specific social influences that shaped this material into what it is and to determine its use-plan than in the case of an end-user product like a car. The steel has only physical micro- and macro-properties and does not, so to speak, carry a use plan with it. One might be tempted to say that a raw material, a component and an end-user product differ in the extent to which the artifact "carries with it its use plan". Nevertheless we have to realize that all these designed objects have a particular intentional (social) history and it is this intentional history that

[3] Of course, the outcome of the two design projects may be such that after all one design is to be preferred above the other. But that is not the point at issue here; here the question is which contextual factors have a definitive or contingent influence on the object of design.

makes them different from objects with the same physical properties but lacking this intentional history (for more details on the constitutive role of intentional features for being a technical artifact, see Kroes 2012).

This difference in visibility or traceability of social features raises the question to what extent design engineers may bracket social influences and concentrate on the 'purely' physical aspects of the technical artifacts they design.

Generally speaking it may be the case that the closer the artifact is to ready-made consumer goods the more difficult it is to bracket the impact of social factors from design practice. But much depends on how well all societal constraints on the object of design have been translated into functional requirements and in specifications that can be stated clearly in physical terms. Suppose that the properties X, Y and Z of the steel to be designed can be stated in purely physical terms, then the design engineers may forget about the functional requirements from which these properties were derived. Then the social (intentional) context of the new type of steel, its intended use, can easily be bracketed or cloaked (for a detailed discussion of cloaking either social-intentional or physical aspects, see (Vermaas and Houkes 2006)). This will be more difficult when the object of a design is, for instance, a car, since it will be much more difficult to express (or operationalize) all functional requirements of a car in purely physical terms. But even if in the case of steel the properties X, Y and Z may be expressed in clear physical terms, social factors may enter the scene, so to speak by the backdoor, because some of the chemicals used to meet the specifications for properties X, Y and Z may be poisonous, expensive, politically problematic or bad for the environment.

Here ends our analysis *in abstracto* of the role of substantive and procedural contexts in engineering design. Its main result is summarized in Table 22.1. We have already noted that the distinction between the substantive and procedural context may become blurred in case the definition of the object of design is changing during the design process. In the following section we will present a description of a real life research/design process in which a change in object of design actually took place. In the final section we will then discuss whether our analysis of substantive and procedural contexts may be of help in understanding the role of social factors in this particular example.

Example: GSBR Technology in Nereda Wastewater Treatment

Having introduced the notions of context and core for engineering design as product and process, we now turn to a real life example of an engineering design project from biotechnology. It concerns the introduction of a new and successful wastewater treatment technology.[4]

[4] Much of the information contained in this section has been collected by one of the authors and colleagues during ethical parallel research on the design and development of this new waste water treatment technology during the period 2004 until 2006 (De Kreuk et al. 2010; Van de Poel and Zwart 2010; Zwart et al. 2006).

On May 8, 2012 the world's first full-scale municipal wastewater treatment plant using Granular Sequencing Batch Reactor (GSBR) technology was put into operation in Epe, the Netherlands. Contrary to more traditional biological activated sludge wastewater treatments, this brand new technology treats domestic and industrial wastewater using *aerobic granular sludge*. In the Netherlands other Water Boards have ordered similar plants, which are under construction. The consultancy firm DHV, which has been the commercial driving force in scaling up the technology from laboratory to full-scale, is building comparable plants in the Stellenbosch region, South Africa, and in Ryki in the southeastern part of Poland. It baptized the new technology *Nereda*. At the opening ceremony, Joop Atsma, the Dutch State Secretary for Infrastructure and the Environment, claimed: "The development of this technology stands as a perfect example of what can be achieved when the public sector, universities and the private sector come together to develop smart solutions." (DHV 2012).

A drawback of traditional biological wastewater treatment plants is their large footprint in terms of space. In these plants water is purified using bacteria flocks, the so-called activated sludge. The low average biomass concentration and the low settling velocities force traditional plants to use large settling tanks. Besides these settling tanks, the plants need other tanks to accommodate the various steps for nitrogen, COD and phosphate removal, with large recycle flows and a high total hydraulic retention time. Moreover to process the surplus sludge from municipal wastewater plants it needs to be thickened and filter-pressed. In the newly developed aerobic GSBR, biomass grows in dense aerobic granules. This means increased biomass concentration in the reactor tanks and improved separation efficiency. The time needed for the sludge to sink to the bottom at the end of each cycle is substantially diminished, which increases the throughput of the installation. The new technology is based on a batch process in which the bacteria that treat the waste water pass through a cycle consisting of a phase of nutrition under anaerobic conditions and a phase of growth under aerobic conditions. This cycle has been chosen in order to promote the formation of stable granules by the slow-growing bacteria.

Apart from their improved settling characteristics, the aerobic granules can cope with nitrogen, COD and phosphate removal in one tank due to their unique layered structure. Because of diffusion gradients inside the granules, the various process conditions usually found in different tanks are now satisfied inside the granular sludge – the plant-in-the-granule concept. The technology uses effectively only one tank without the need for large recycle flows. Theoretically these granules can reach high removal rates, namely 100 % organic carbon removal, 90–95 % of phosphate removal and 90–95 % of total nitrogen removal with 100 % ammonium removal (De Bruin et al. 2005; De Kreuk et al. 2005). Feasibility and design studies showed that the required land area of traditional waste water treatment plants can be reduced by 80 % and the energy needed can be decreased more than 30 % because of a decrease in construction material and energy needed during building and operation (De Bruin et al. 2004).

Before we delve deeper into the history of this technology, let us present a brief overview of the main parties that have been involved in the design and development of Nereda. The GSBR technology has been developed by Mark van Loosdrecht and his colleagues at the Department of Biotechnology (Kluyver Lab.), Delft University of Technology, the Netherlands. After successful laboratory experiments, Van Loosdrecht, approached various governmental and private organizations to gather funds for the further development of the technology. STOWA, the Foundation for Applied Water Research in the Netherlands, proved willing to invest in the scaling-up of the three litres laboratory reactor to an outdoor pilot plant of 1.5 m^3. STOWA is an organization of the water boards, the local authorities responsible for sewage treatment in the Netherlands. STOWA finances research on new treatment technologies. Van Loosdrecht also acquired funds from STW, a governmental agency stimulating and promoting innovative academic research, for a Ph.D. research project that was carried out in parallel to the pilot plant research. Finally, DHV, an international engineering and consulting firm, with water management technology as one its main domains, showed interest in the commercial exploration of the GSBR technology. DHV was in charge of the research at the pilot plant.

The history of research on GSBR technology goes back at least to research on anaerobic sludge for waste water treatment during the 1970s. Anaerobic Granular Sludge was known to be formed in Upflow Anaerobic Sludge Blanket (UASB) reactors used to produce methane while treating wastewater using an anaerobic process. A blanket of granular sludge was formed which starts to reach maturity after 3 months and suspends in the tank. This blanket contains dense compact granules with a particle size larger than 0.75 mm. Lettinga from Wageningen University in The Netherlands is well known for his late 70s work on UASB reactors. Expanded granular sludge bed (EGSB) digesters are waste water treatment systems similar to the UASB reactors. At the start of the 1990s *aerobic* sludge research was given a boost by the hypothesis of Mishima and Nakamura claiming that also aerobic filamentous bacteria could mutually entangle into aerobic granules. It turned out that aerobic granules could be formed but the explanation of the process remained controversial. For anaerobic granules it was suggested that bacteria stick together into granulates because of mutual exchange of indispensable nutrients. Aerobic bacteria are autotrophic and perfectly capable to live on their own. So why would they agglutinate into granules? At the end of the 1990s researchers started to theorize about the answer to the latter question (we will return to the issue of aerobic granulation below). At the same time researchers started setting up the first lab-scale aerobic granules experiments (Morgenroth et al. 1997; Beun et al. 1999; Dangcong et al. 1999; Etterer and Wilderer 2001), and from the start of the twentieth century interest in aerobic granule research increased and pilot scale studies started to be carried out. The history of the GSBR technology and of Nereda is to be placed against the background of this scientific and engineering interest in aerobic granular sludge in waste water treatment.

Van Loosdrecht and his colleague Sef Heijnen became interested in what later became the GSBR technology after a 1996 visit to colleagues in Munich who were working on Sequential Batch Reactors (SBR). They thought about how they might combine their own experiences with airlift reactors with SBR's. SBR's are processing tanks for a five stage treatment of batches of wastewater. They were not primarily directed towards the production of granular sludge. However, SBR's were suitable to make smooth rounded particles so perhaps they could be used to create aerobic granular sludge in a SBR.

After their Munich visit two issues became prominent on the research agenda of Van Loosdrecht and his colleagues, one of a scientific, the other of an applied nature. The scientific issue concerned the biological explanation of the development of granular sludge. Anaerobic granulation was biologically explained: anaerobic bacteria stick together because of their mutual exchange of indispensable nutrients. But aerobic and autotrophic bacteria were also shown to granulate. How can this be explained biologically as they are perfectly capable of living on their own? According to Van Loosdrecht the formation of aerobic granules undermined the biological collaboration theory of granulation for anaerobic granulation; at least it could not provide a general explanation of granulation. Another explanation attempt, which focused on the extracellular matrix of proteins in the granules, could be used to explain granulation for the aerobic and anaerobic case. But according to van Loosdrecht this matrix is indeed important for the structure of the granules but not for the granulation process. Van Loosdrecht wanted to show that even the fastest growing (aerobic) organisms could granulate and that mechanical shear forces in a reactor are decisive for granulation. For this reason, he set up a research project (performed by Beun, and financed by NWO) with the aim of comparing granular formation in an airlift and a bubble column in which the shear forces are different. The outcome showed that fast growing organisms granulated in an airlift but resisted granulation in a bubble column. So, this research showed a clear influence of shear on growth rate of the organisms: the lower the growth rate gets, the less shear is needed to produce granules. Moreover it showed on a laboratory scale the possibility of an aerobic granular sludge airlift reactor.

The second, application-oriented issue concerned the structure of the granules of the sludge. People were producing aerobic sludge with autotrophic nitrifying granules but they did not succeed in producing aerobic granules with an anaerobic core of heterotrophic bacteria. Van Loosdrecht and his colleagues wanted to develop granules with a layered structure, with an aerobic outside layer where nitrification could take place and an anaerobic zone in the center taking care for the denitrification by heterotrophic organisms. With the help of such granules it would be possible to combine two stages in traditional waste water treatment.

After the possibility of an aerobic granular sludge airlift reactor had been demonstrated in the laboratory, Kreuk carried out another research project that aimed at scaling-up the aerobic granular sludge technology from the laboratory acetate set-up to pilot plant scale using real waste water (in the period 2000–2004). It was funded by STOWA and STW. In fact, work on scaling-up issues had already begun earlier, when the laboratory work of Beun was still on its way. Van Loosdrecht approached several engineering firms as a result of which a major engineering firm in the Netherlands, DHV, became involved in the scaling-up research. An application for a STOWA grant was written in the second half of 1998. STOWA combined the Delft aerobic GSBR proposal and another proposal stemming from the University of Wageningen into a compact reactor innovational research incentives scheme. Doing so, they allowed DHV to carry out a more precise and specific tentative feasibility study. By changing the technology somewhat and calculating the costs, DHV managed to put the technology in a financially more attractive perspective. Accordingly, the engineers were allowed to pursue the project and thus the GSBR connection between DHV and the Kluijver Laboratory came about. Because STOWA and DHV were both most interested in household sewage water treatment, the latter became the main focus of the aerobic GSBR project. This focus was not fixed at the outset.

In 2002 the STOWA compact reactor scheme came to an end and was finalized with a full-blown feasibility study for a real scale aerobic GSBR household sewage plant. The study was positive about the real scale possibilities of the new technology. For this reason STOWA wanted to proceed with the development on pilot scale and provided DHV with financial means to do so. The pilot started in 2003 in Ede. STW was not involved in financing the pilot, which was too practical for their standards, but they did finance the research of Kreuk, the Kluyver Lab participant in the project who was dealing with practical and theoretical up-scaling questions on a daily basis.

As was more or less its standard practice, STOWA installed a Supervisory Committee (SC) to monitor the progress of the project. Its members were representatives from STOWA, STW, the Kluyver Lab, HDV, the water boards as being potential users of the GSBR technology, and members of other engineering firms. The SC was to act as a forum where actors from the network, and some stakeholders from outside the network, could meet to have discussions and make relevant research decisions. The committee did not have a formal decision-making procedure in place, but it influenced research and development decisions by providing a forum for negotiations between the actors. All in all, the SC had three functions. First, it was to control the quality of the research and the progress of the project. Second, it provided oversight so that, besides the scientific knowledge acquired, the practical and applied knowledge was also published in a clear and explicit way. Third, the SC was to function as a critical sounding board.

One of the issues discussed in the SC concerns the problem of the production of granules in the GSB pilot reactor. The engineers/scientists had produced granules in the Kluyver Lab on small scale (3-liter reactors), at room temperature using acetate and not real sewage water, and using an airlift reactor. At the pilot circumstances were very different. Besides the difference in volume, the working temperatures were significantly lower and the substrate was real sewage wastewater instead of acetate. As a result of these different circumstances the granules in the pilot were showing up very slowly. Moreover, the people involved in the scaling-up project tended to talk in terms of granules but these were of such small dimensions that the external specialists only saw flocculated sludge. This question became an important issue at the end of 2003 when the Sludge Volume Index (SVI; the sludge volume index is an important measure of sludge settleability and thus for granule formation) were difficult to measure because of sludge flotation (STOWA report of januari 8, 2004). This flotation was not a sign of firm granules. The lagging behind of the granulation process provoked serious discussions about changing the criteria and specifications of the GSBR technology. DHV and the scientists were asked to provide a new version of these criteria. Among other specifications the first proposed version regarding granulation stated: “stable and significant lower SVI” than measured before (SC minutes, Jan 15, 2004). Of course, the researchers did not want to put themselves in a straightjacket during the process. The SC was not satisfied, however, and they started a discussion about the definition of the granules. This discussion resulted in go/no criteria which only concerned granulation. The criteria decided upon at the SC of May 18, 2004 read:

1. The fraction of dry matter should be at least 15 kg/m^3
2. The SVI after 5 min should be around 50 ml/g
3. Half of the substance sludge/granules should consist of granules with minimal diameter of 200 μm (SC minutes May 18, 2004)

Although the lower limit of the granules seems to be modest relative to the granules produced in the laboratory, the go/no go episode and its definition of granulation clearly illustrate that the SC took its role seriously.

Actual work on the pilot installation started in 2002 and ended in 2005. In 2002 the pilot set-up in Ede started with one airlift and one bubble column reactor to compare their performances. In June 2003, however, the set-up of the airlift reactor was transformed into a second bubble reactor and today’s full-scale technology is based on bubble column and not on air-lift reactors. Thus, the decision to change the core of the technology into bubble column reactors has had a decisive influence on the final design of the waste water treatment installation. Interestingly, the choice between the two types of reactors is closely related to at least four different issues or factors, viz., the scientific experiments about the role of shear forces in granular growth; the working principle of the granulation; considerations of financial and energetic costs, and finally the network-of-actors involved in the collaboration.

Let us first have a closer look at the difference between a bubble column and an airlift reactor. A bubble column reactor is just a container in which air is pumped in from the bottom. An air-lift reactor is a bubble column reactor with an additional (internal or external) feedback loop for the liquid. The air bubbles force the liquid to rise from the air inlet at the bottom of the reactor and to go down in the feed-back loop where no air bubbles forces it to rise. The feedback loop ends again at the air inlet. Obviously, an airlift column is more difficult to build but has better circulation and oxygen transfer characteristics. Moreover it provides higher and more equally distributed shear forces between the granules and the substrate in the reactor. At first sight, the design decision between the two working principles depends primarily on the balance of the extra costs of an airlift reactor against the advantages of better oxygen and shear-force characteristics. A somewhat closer look, however, reveals interesting interdependencies regarding the four issues mentioned above.

We have already come across the issue of the role of shear forces on granular growth. Van Loosdrecht initiated research into this issue because he had serious doubts about the prevailing explanation of anaerobic granular growth. Experiments performed at the Kluyver Laboratory showed that shear forces in airlift reactors were high enough to impede fast growing aerobic bacteria to grow in flocks and to stimulate the growth of granules. Since they stimulate granules production, and shear forces in an airlift column are higher than in a bubble column reactor, scientifically airlift reactors are preferred to bubble columns for granulation. However, the issue of the influence of shear forces on granular growth rate did not in the end decide the choice between and airlift or bubble column reactor.

Another issue of paramount importance was the oxygen concentration in the reactor. Most successful experiments with aerobic granules at the start of the twenty-first century operated under relatively high oxygen concentration and constant aeration. For nitrogen removal, more specifically for denitrification, and for lower energy costs during operation low oxygen concentration was necessary but these low concentrations rendered the granules unstable (Mosquera-Corral et al. 2005). Earlier experiences with biofilms had shown that slowly growing organisms had a stabilizing effect on biofilms. Consequently, Kreuk and Van Loosdrecht argued that for the full-scale reactor to work under low oxygen concentrations the total organism growth rate should be decreased during one cycle. They lowered the growth rate by ingeniously letting the "feast phase", where growth is on an external substrate (nutrients), be preceded by a "famine phase", where the organisms feed on nutrients that are internally stored. The introduction of the famine phase in the bubble reactor was successful. Kreuk showed granulation to occur in bubble columns if the phase of aerobic growth started with a famine phase, that is, a period of anaerobic feeding. Still the airlift reactor outperformed the bubble column since the first produces granules already after 5 days whereas with the latter it took a month before granules occurred. As the famine-feast regime, which became one of the operating principles of the final design, selected organisms with a lower growing rate, the influence of the shear-growth-rate principle established by the research of Beun implied that the shear was an important ingredient for granulation in aerobic systems.

In spite of these laboratory results, an airlift and a bubble column reactor were put in parallel to compare their performances at the pilot plant in Ede. Apparently the researchers and scaling-up engineers did not know how these laboratory results would translate to pilot-scale conditions. In the pilot set-up with two reactors of 6 m high and 0.6 m diameter granule growth turned out to be very disappointing. Moreover the SVI measurements of the airlift and bubble column were comparable although those of the first were somewhat better than those of the latter. These outcomes made the SC decide to transform the airlift reactor into a second bubble column and to concentrate on granule formation. This decision was decisive for the final Nereda aerobic GSBR design.

Finally, according to Van der Roest, the project manager at the engineering firm DHV, the decision to opt for the bubble column reactor was made by DHV and DHV had to convince Van Loosdrecht to abandon the airlift reactor, who did so only reluctantly. From the point of view of Van der Roest, if it had not been for DHV to abandon the airlift reactor the aerobic GSBRs would never have come to the commercial market. According to Van der Roest, he had to challenge the scientists to adapt the process for practical purposes. He had to make the scientists aware that on real scale the oxygen concentration would be lower than in the laboratory because of restrictions on pump capacity. From the perspective of the Kluyver Lab it was evident that bubble column reactors were less complicated and thus less expensive than airlift reactors. DHV calculations clearly showed the extra costs of airlift technology. However, in the eyes of the scientists DHV had not gone far enough in technologically optimizing the standard airlift construction and to adapt it to the new GSBR technology. The extra start-up costs could have been reduced. The crucial question, however, would remain whether these extra costs balanced the savings in operational costs regarding energy and after treatment. This was almost impossible to predict especially if one realizes that the after treatment is very expensive.

Discussion

In this final section we will use the GSBR example as a test bed for our interpretations of the notion of context of design as process and as object. Before we apply our conceptual framework to this case, we have to take into consideration the specific nature of the Nereda project. The Nereda technology is an example of what Vincenti (1990) calls *radical design*: it is a design based on a new working principle and its development was strongly research driven. In that respect it is different from normal design, which is involved in run of the mill (industrial) design projects in which (minor) variations on existing designs are developed and in which research plays only a minor role. We expect that if our conceptual framework is of help in understanding the bearing of contextual factors on the object of radical design, as in the Nereda case, then it may also be fruitfully applied to cases of normal design. This expectation is based on the fact that the pivotal distinction of our conceptual framework, namely between process of design and object of design, forms the basis of almost all schematic diagrams of the design processes developed and employed by engineers, and the fact that these diagrams are primarily intended to cover cases of normal design. But, of course, this expectation would have to be borne out by further research.

In line with the characterization of Nereda as an example of radical design, the case study strongly suggests a differentiation between at least *two* kinds of objects that scientists and engineers were working on. In the first place, there is the sewage water treatment plant as object of design in the sense of section "Substantive and Procedural Contexts of Design". There we characterized the object of design as descriptions in terms of blueprints, texts or all kinds of models of at least (1) the artifact itself, i.e., its structure, its function and its working principle, (2) its interface with the outside world, and (3) its 'use plan'. We will refer to (1–3) as the *final design* of an artifact. Besides this object of the treatment plant design, there is also an *object of research*, namely the working principle on which to base the sewage water treatment plant. In the course of the development of Nereda both objects played an important role.

Let us first have a look at the object of design in the Nereda case. In hindsight, the object of design is the final design that was implemented in the first full-scale operating plant using GSBR technology. This 'backward' looking determination of the relevant object in the Nereda case is, however, rather one-sided. It is not a characterization of the object of design that may fruitfully be applied to the early stages of the development of this technology. In view of the fact that these early stages were strongly research driven, it might be more appropriate to introduce the second object of the Nereda development mentioned above, viz. the object of research during the early stages, which gradually was transformed, co-elaborated or accompanied by the object of design.

How are we to distinguish more precisely between the object of design and the object of research in the Nereda case? We are primarily interested in characterizations of these objects that are valid from a 'forward' looking perspective, which means that they may function as goals driving the development of Nereda (where different stakeholders may have had different interpretations of these goals). One of these goals is the production of aerobic granules with aerobic organisms at the outside and anaerobic organisms in the core, using a batch process which might be used to purify wastewater in one reactor; we will refer this goal as the *GSBR-working principle*. Purifying here means oxidation of organic matter and ammonium, nitrate reduction, and biological or chemical phosphate removal etc. Another one is the engineering-scientists' goal of the proof of concept of the GSBR-working principle, the feasibility of which was proven in the laboratory. Finally, there was the practical goal of the engineering firms and water boards who wanted reliable, effective and economic – less energy and land use – wastewater treatment plants based on the GSBR-working principle. This difference in goals made STW subsidize the Ph.D. proof of concept research in the laboratory and STOWA finance parts of the pilot-plant research. In the following we take the object of research in the Nereda case to be the proof of concept of the GSBR-working principle, and the object of design to be the final design for reliable and effective sewage water treatments plants based on the GSBR-working principle.

Interestingly, the notion of the object of research still leaves open whether to use an airlift or a bubble column reactor in the object of design. The GSBR-working principle as the core of the object of research fixes a number of important design characteristics and parameters (for instance, use of aerobic granules and one reactor tank). Defined in this way, the core of the object of research may be taken to constrain the 'technological space' within which the object of design has to be developed. This research object determines the GSBR-technology but not the final design (blueprints) of a Nereda plant. Within the technological space defined by the working principle a design based on airlift and bubble column reactors are still possible. This, however, does not preclude that further scientific and technological considerations may decide the choice for one of these types of reactor in the final design (building plans).

Given our analysis of design as object and design as process in section "Substantive and Procedural Contexts of Design" and our interpretation of the object of research and the object of design, how can we fill in Table 22.1 for the Nereda case? As always, real life turns out to be much more complicated than our abstractions of it. Our case description clearly illustrates the difficulties of projecting our abstract concepts onto this real life engineering design case. Nevertheless, we will make an attempt.

Let us focus first on the kind of factors that played a role in the substantive context of the final design of Nereda. One of the main ingredients of the substantive context is the decision to develop and use the GBRS technology. This decision, which was taken by the various parties involved in the Nereda project, was made in a network of collaboration, without centralized power relations, between scientists, engineering firms, users and subsidizing partners. The reasons to opt for the GBRS technology, and thus to constrain the object of design to this technology, are directly related to the proof of concept and the possibility created by GSBR technology to reach the practical goal of a sewage water treatment facility that was smaller, less energy consuming and at least as effective and reliable as traditional treatment plants. Within the network of collaboration the SC played a key role in the communication between the various parties. As the design project was on the way, negotiations between these different stakeholders in the SC led to various modifications in the object of design. The SC added new criteria and modified existing specifications. The setting of the go/no go criteria serves as a paradigmatic example of fixing the constraints or specifications of the object of design. All decisions and developments regarding design criteria belong to what we have called the substantive context of the design object, including the decision to try to implement the GSBR-working principle for waste water treatment. The fact that laboratory experiments had shown the feasibility of the working principle (the object of research) did not by itself imply that a design project should be set up.

Now let us turn to the object of design, it is the final design of a Nereda plant. What features of this design may be considered to be determined by engineering design proper and therefore belong to the core of design as product, or to engineering design proper? In our opinion, these are all design features that may be fixed on the basis of scientific and technological considerations given the constraint of using the GSBR technology and of coming with an effective and efficient final design for a sewage water treatment plant.

It should be noted that the distinction between the object of design and its substantive context is more intricate than suggested above. Take the decision to use a bubble column reactor and not an airlift reactor. This has been an important decision for the final design. Is this decision to be interpreted as a contextual factor, a factor that influenced the design of the GSBR technology from the 'outside', or as a decision that was taken from 'within', that is, within the technological space and that was based on technological considerations. Van Loosdrecht's opposition to this decision may be interpreted as finding its origin in his idea that there were convincing internal scientific or technological reasons to opt for the airlift reactor, and consequently from his perspective the decision to use the bubble column reactor was forced by reasons originating in the (substantive) context of the object of design. According to Van der Roest (DHV), however, the design decision was based on practical purposes; in his opinion a design based on an airlift reactor would never have reached the commercial market. At first sight, these market considerations may be considered to be of a contextual nature but that remains to be seen. The whole GSBR project was intended to be a practical alternative for traditional technologies used to treat waste water and from that perspective all constraints that derive from this goal of being a practical alternative are definitive of the object of design, also the constraints derivable from market considerations. Van der Roest might, therefore, argue that given all constraints on the object of design the bubble column was the only scientific or technologically feasible option. From that perspective the decision to go for this type of reactor becomes a decision from within the technological space. Consequently, to interpret the bubble column reactor decision as a contextual or a scientific/technological design decision depends heavily on how the object of design is conceived, that is, which factors are taken to be relevant for, or go into the definition of the design object/problem.

Let us turn to the process of the Nereda design and first ask ourselves: What is the core of this process, that is, what are the main actions and considerations that were believed to bring about an adequate solution to this design problem? The core of the Nereda design process, as far as its substantive content is concerned, has been the scaling-up strategy from laboratory scale, via pilot plant scale to full-scale systems development. It was believed that if the proof of concept of the GSBR-working principle in the laboratory succeeded, the concept could successfully be scaled up to full-scale and ensuing actions were undertaken. Depending on the specificity of the working-principle formulation, we may claim that in the course of the up-scaling the working principle changed somewhat from airlift to bubble column reactor. However, this substantive content is not to be confused with the core of the design process as defined in section "Substantive and Procedural Contexts of Design". There this core was defined as the kind of actions (and their order) as prescribed by the flow diagrams of design methodology. This notion of core of the design process may be applicable to cases of normal design but seems hardly applicable to this case of radical design in which research and design activities are so closely intertwined. Nevertheless, some remarks about the procedural context of the Nereda design process may be made. All decisions about the means and resources to solve the research and design problems belong to this context. Clearly, everything that had to do with fund raising and finding interested commercial partners to develop the laboratory technology to full scale is part of the procedural context. In addition, decisions by the main scientists to devote research capacity in the laboratory and at the pilot plant to carry out feasibility and scaling-up research belongs to the procedural context. Also the installment of the SC belongs to this category.

Although the distinction between design process core and context is difficult to make, the following shows that it does play a role in design practices. Design engineers and methodologists have written numerous books and articles that discuss various flow diagrams about how to structure design projects such that design problems may be solved in a systematic way. The basic idea behind these flow diagrams is that there are good and bad ways to try to solve a design problem. These flow diagrams may be considered to describe the core of design as a process. Whether or not there actually is such a core (or only one core/design method, or several) is a matter of controversy. Nevertheless, most design engineers would probably subscribe to the following remarks by Hales (1993, p. 17):

> One of the most frustrating things about being a design engineer or design manager is the way projects are manipulated by those who have very little to do with the design process

itself. One minute everything is extremely urgent and the next minute the project is no longer required or the money has run out. More and more influences affect the course of design projects.

Hales' remark clearly suggests that many influences on the design process are experienced as coming from outside the world of design and "have little to do with the design process itself". So, somehow a distinction may be made between what legitimately belongs to the inside or core of a design process and what to its outside or what we have called its procedural context, even if it is in fact very difficult to spell out the specific details of this core. Some of the frustrations referred to in the Hales quote can be found in the words of van der Roest when he claims: "The first Nereda purification plants could have been up and running years ago if a guarantee fund had been available" (Wassink 2011). It may at least be safely concluded that often considerations of the funding of design processes belong primarily to its procedural context.

It may be rather problematic to become more specific about core and context regarding the daily developments in the Nereda case because the whole process did not start with a design brief or an assignment of some client. Undoubtedly in the final stages of the development of the full-scale plant, there will have been some process that started with a design brief and for which some kind of method for solving that design problem was used. But whether our distinction between the core of design as a process and its procedural context can be fruitfully applied to this design project remains an open issue.

Let us briefly summarize our main results. Kroes and Van de Poel (2009) have argued that it is not possible to make a neat distinction in general between technology on the one hand and its social (intentional) context on the other since some social phenomena are definitive (constitutive) for technology. This leaves open the question whether it is possible to delineate those social processes that are internal (definitive) or external (contextual) to technology. In order to explore this problem we have introduced a distinction between core and context of design as object and as process. To see whether these abstract distinctions make sense in real life engineering practice we have tried to apply our distinctions to the case of the design and development of a new kind of sewage water treatment technology. Our analysis makes clear that while *in abstracto* a distinction between core and context of design as object and process may seem plausible, it may be very problematic to apply this distinction to actual engineering practice and to characterize a particular design feature as the result of internal (technological) or external (social) factors.

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