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Chapter 3

Product Sound Design: Intentional and Consequential Sounds

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Additional information is available at the end of the chapter

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1. Introduction

In our daily life we are immersed in sounds that are generated by products. If one were to ask someone to name sounds produced by products, often sounds are mentioned that alarm or inform us (e.g., microwave oven beeps, telephone rings etc.). These are the sounds of which we are consciously aware. However, many sounds subconsciously play an important role in our interaction with a product. One hears if the battery of a toothbrush runs out of power; one hears the power of a vacuum cleaner and one hears if the bag is full; etc. Although these are all functional aspects, sound also plays a role in our aesthetic, quality, and emotional experience of products. For example, one hears if the sound of a car door evokes a sense of quality. Car manufacturers have acoustical engineers to make sure that a slammed door will evoke this sense of quality. Sound quality and its relation to perception have been studied to some extent (e.g., Blauert & Jekosch, 1997; Bodden, 2000; Lyon, 2003). Often, these methodologies cover only one aspect of the design or evaluative process. Here we present a systematic approach to the inclusion of sound in the design process and its use as an essential aspect of controlling the quality of design and as a means of educating designers (and students) about the constituent parts of a product.

In this chapter, we will distinguish between sounds that are generated by the operating of the product itself and sounds that we intentionally add to a product. In the field of product sounds the first category has been named consequential sounds and the second category has been named intentional sounds (Van Egmond, 2007). This distinction is essential - both categories of sounds will require different design methods and the use of knowledge of different disciplines is needed. Intentional sounds are mostly composed which may be experienced as musical sounds. One could state that the use of intentional sounds as feedback of alarm sounds

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is in fact creating a small musical composition (i.e., musical motives). Therefore, these sounds can also be used to convey brand values of companies.

Consequential product sounds are experienced as "noisy". It is very difficult for users, for designers, and for acoustical engineers to verbally express how they experience a sound. Several problems exist. In general, users lack the vocabulary to express themselves to explain what is wrong or right with a sound. They normally will say the product makes a unpleasant sound or noise. Designers also lack the vocabulary to express design concepts that may also be used in the design of a sound. The acoustical engineers have a very technical vocabulary from the disciplines of physics and sometimes psychoacoustics, which does not communicate very well to designers and to users. In addition, to understand the aesthetic and emotional experience of product sounds knowledge from the field of psychology (auditory perception, cognition, and emotion theories) is needed. As stated before, product sounds are loud and noisy. This inherent property makes it difficult to describe the sound in a structural manner. The reason for this is, of course, that noise by itself is random and lacks structure. However, product sounds do not produce completely random noise due to the resonance and engine/boiler properties of products (of course, there are many sources that are responsible for the generation of sound in domestic appliances). It is the aim of this product sound course of Industrial design Engineering(IDE), Delft University of Technology (DUT) to try to relate descriptive aspects from the physical, perceptual, and experiential domain to each other in order to improve the sound of domestic appliances.

1.1. The perception of sound

The top-down processing (involving knowledge stored in memory or mental representations) will result in the attribution of meaning (e.g., recognition, identification), relating sound to certain events, evoking (cognitive) emotions. It is important to note that the sensorial experience of a sound can be — often — directly related to the spectral and temporal features of a sound, whereas this is more difficult for top-down aspects (except for very well-structured sounds like speech and music). As described above, one of the aspects that is well known is the irritation that sounds evoke. The irritation can often be contributed to the sensorial processing of the sounds. It can be argued that top-down aspects, like the attribution of meaning, can positively influence the experience whether a sound is irritating or not.

In courses, students hear the sound of an epilator. This sound evokes a rattling and rough experience. If the students are asked to tell the source of the sound most students say this sound stems from a hedge-trimmer or some other power tool. If they are told that it is an epilator and they listen to the sound for a second time, the look on their face is completely different and reveals a sense of unpleasantness. Thus, the experience of a sound changes if the meaning is known. One of the perceptual aspects that cause this is the rattling of the product caused by the construction, the gears, and the engine. This aspect can be captured by the measure of roughness. This attribute can be related to the structural properties of the sound in spectral and temporal domains and is one of the determinants in the perception of sensory pleasantness.

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2. Products

A product is the result of a design process that starts with a design problem, involves ideation phases, and ultimately leads to a market introduction. In the context of product sound design, mainly domestic appliances are considered. The appliances have moving parts that can move linear or radial and are joined together in such a way to fulfills its functional aspect. and in particular the sound of the product. The product sound is influenced by many physical parameters such as: material, size, form, stiffness, load, energy etc.

2.1. Technology

Energy facilities are dependent on the place of use. For instance a product with a combustion engine is not used in houses or factory halls, because the pollution of the environment and sound intensity. Electricity is the most convenient energy type which is available in the form of batteries and power outlet. All other types of energy such as, hydro-electric power, fuel cells, human power, solar energy and atomic energy are not considered because the main power source is electricity. Electricity is easy to convert into another type of energy such as: thermo energy, mechanical energy, chemical energy, etc., but every conversion means an energy loss.

Product sounds manifest themselves in mainly three sources airborne sound, liquid sound and structure-borne sound. In a product we are dealing mainly with structure-borne sound sources that find their way to the outside environment by radiation. Transfer paths take care of the propagation of the sound from the source to the environment of the product. Structure-borne sound demonstrates itself in solids, in constructions that are built up from plates, beams, shells and shafts. The material properties determine the propagation speed, which is constant for certain waves and forms. The propagation speed depends on elasticity, specific gravity and contraction, which is different for solid materials. However, steel and aluminium have the same propagation speed because the division of the elasticity by the density is the same (E/ϱ).

Medium	Prolongation speed in m/s
Air	340
Water	1500
Steel, Aluminium	5200
Iron	5200
Brass	3700
Glass (window)	6800
Wood (parallel) ρ=0.5 kg/dm^3	4000
Lucite (Plexiglas)	2650
Polystyrene	2300
Rubber (soft)	50

Table 1. Propagation speed for a number of materials, liquid, and air (Verheij, 1992).

The size of a product is determined by the required function and power needed to fulfil the function. For instance, a toaster: the electricity is converted into heating power for toasting the bread. The size of a toaster depends on the efficiency of the reflection and isolation of the power. The heating element is a sound source. An additional sound source is the relief mechanism.

The bending stiffness is the elasticity (E) multiplied by the moment of inertia (I) which is dependent on the cross-section type and the dimensions. For instance an electric milk shaker has a bar with a certain mass on the end. If the bar turns around then it is bending under the gyroscopic force. Better bending stiffness could be achieved if a hollow profile is used. This is because the mass is further away from the centre of gravity. The bending energy is dependent on the stiffness but has a lower bending stiffness means a higher bending energy. This bending energy is transformed into sound.

A load is needed to fulfil the required mechanical function for a right performance of the appliance at a certain speed. The power required for the function fulfilling is the load a torque (T), that is necessary for processing times the speed (ω). The needed power out, Pout= ω x T. The power input multiplied by the efficiency of energy transforming η_{et} and mechanical transmission η_{mt} is, Pout = Pin x η_{et} x $\eta_{mt..}$ The choice of type of power and mechanical drive is really important for the overall efficiency η_{eff}. If the efficiency of the permanent magnetic motor is 50% and the mechanical drive 80% for each transmission in a three-step drive, then the efficiency is only 25.6%. The conclusion could be that the best drive is the one without the mechanical transmission, so the energy transforming is only responsible for the efficiency. The biggest advantage of a direct drive is less parts, which reduce enormously an amount of sound sources. The efficiency of a product depends on the energy losses which are transformed through friction into heat, and the movements of masses in sound or noise.

Moving product parts are necessary to fulfil the function of domestic appliances which have six degrees of freedom in a three dimensional space, three degrees are transversal and the other three are rotational. The complete drive of a domestic appliance consists of an electric motor with a mechanical transmission that will be built up with machined parts to adjust the revolutions per minute that is needed with a certain torque. The best drive is without any moving parts, the direct drive. For example, a gear shaft has only one degree of freedom, namely rotation around its own axis. All the other degrees of freedom will be restricted to zero by the construction. For this purpose, fixed, detachable, and combination joints are available. A certain clearance is needed to realize their relative movements. A minimum and a maximum clearance can be determined depending on the tolerances of two parts, as well as small expansions due to temperature increases. Tolerances are the result of the chosen manufacturing process, which is determined by material, shape, size and volume of production. The clearance in the joints of the parts has a certain freedom of movement of the masses. This costs an amount of moving energy which will be transformed in a product sound.

2.2. Product domains

The product has relationships with three domains: Design, Embodiment and Production (see figure 1). The domains have a relationship which three conditions: environment,

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designer, and manufacture. The relationship between the domains are the activities: Creating, Designing and Making.

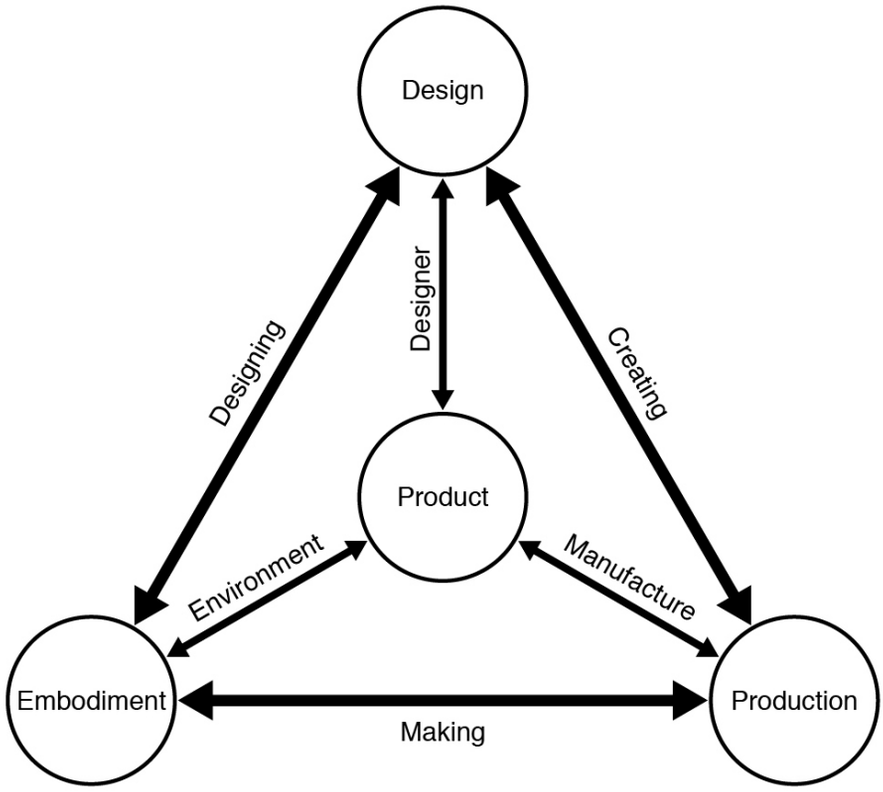


Figure 1. Figure 1: Product relationship with the domains production, embodiment, and design.

Each domain is associated with different levels see table 2. The domain design associates the user, observer and owner level. The domain product points out the physical, sensory and social experiences (after derivation of design from the consumer's point of view (Heufler, 2004). The two other domains have also pointed out the levels, the levels are for embodiment: practical, aesthetically, and status symbol. The levels are for production: parts making and assembly, availability, and benefit. The eye catcher is 'benefit' at the domain production, because without any profit, no other activity shall be undertaken which results in the production of products. Investments are made in production and design. Finally the activities should be profitable in a given period.

Design	Product	Embodiment	Production
User level	Physical experience	Practical	Parts making & Assembly
Observer level	Sensory experience	Aesthetically	Availability
Owner level	Social experience	Status symbol	Benefit

Table 2. Domains with their levels.

The relationship between design and production is the activity creating, or availability of production facilities. The availability is necessary to create the production under the constraints of the part design, manufacturing process and material. The designer must have good knowledge of: manufacturing and assembly, material, and aesthetics to create a successful product sound design.

The relationship between design and embodiment is the activity of designing, which is mostly carried out by a designer. Note that, designing is not engineering but creative problem solving, which always results in an embodiment. Engineering is a structured way of solving problems which lead to technical solutions that result in, objects, or systems.

The relationship between embodiment and production is the activity of making, the realization of a product with machinery or manually with a set of tools. Making gives satisfaction to a designer that a product can be realized. This experience is increasing the personality and identity of designer. The conditions form the relationship of the product with the domains of design, production and embodiment. Manufacturers make it possible to realize products by means of production This condition is an important connection in the product realization process. The designer is the condition to realize the product from a design. However, there are differences in the quality of the product design. This is caused by the personality and identity of a designer. The environment is the condition that an embodiment can be manifested as a product. The product should be manufactured from raw material to parts which will be assembled as a whole. This may be a component, a sub-assembly or a product. Two kinds of tolerances occurred, which are known as dimensional tolerances and geometric tolerances, in manufacturing of parts and in the assembly of parts into a whole. Every manufacturing process has its own tolerances that depends on material, type of process, stiffness, geometry etc. For steel and aluminium the ratio E/ϱ is almost equal, so also sound prolongation speed. Elastic modulus is always influencing the stiffness coefficient EI with I as moment of inertia, which results in dimensional tolerances and geometric tolerances. However, the manufacturing process speed and force have influence on the size of tolerance, but not on geometric (form). The power of the manufacturing process is transformed is force and speed, which the temperature of the work will rise higher. The height of temperature is dependent on the power needed for the process and processed material. It results in temperature elongation, which influenced the tolerances after cooling of the work to the temperature of the environment.

The designers make the manufacturing process choices which depends on material, shape, size and volume of production, which results in certain dimensional and geometric accuracy. After assembling two parts, the clearance will manifest as a result of the separate accuracy of these parts. For instance for plastics it is harder to reach the accuracy, because the temperature elongation is much higher than that of steel. For instance a folding plastic garden chair should be able to fold up, which is made possible by hinge points which are required if the parts have to move freely. The chair does not have a power source to conduct, but has a force to hold. Here, large tolerances are acceptable while the comfort is not being affected. With plastic, these tolerances are achievable despite the poor accuracy of the manufacturing processes. Shape of a part is to be achieved by cutting, extrusion, forging, moulding, casting, stamping, forming etc. However, not every material is applicable for every manufacturing process. But the size

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always has limitations resulting from the starting material, for example wood is limited by the age of the tree. The volume of production can range from single pieces to mass; this requires constantly changing of the manufacturing processes and thus different clearance requirements are possible. At mass production, the tolerances are under control; otherwise the failure rate is too high. Zero defects is possible with mass production. However, before this is achieved, the entire production system must be calibrated.

The manufacture makes the parts between the upper and lower limits of the tolerance. The clearance between two assembled parts will be between maximum and minimum size of the individual components. A minimum clearance is preferred because the excitation has than the smallest movement, and the smallest influence on the components, resulting in a lower sound pressure. Of course it is unique to reach this situation by means of a manufacturing system. Most clearances are reached between averages of the tolerances. Every domestic appliances produce sound. The production of these sounds is a consequence of their operating and construction. Therefore, these sounds are called consequential sounds. These sounds should be analysed in the physical, perceptual, and emotional domain to relate subjective findings to the engineered parts of the product.

If a domestic appliance is switched on then the power will conduct through the construction of parts to fulfil the working principle. Efficiency of the function is never hundred percent the losses are raised by friction of moving parts and vibration of parts, by mechanical excitation of the construction.

2.3. Consequential product sound model

The consequential product sound model are shown in figure 2, with four main aspects: sources, transmission of sound in the product, radiation, and transmission to receiver.

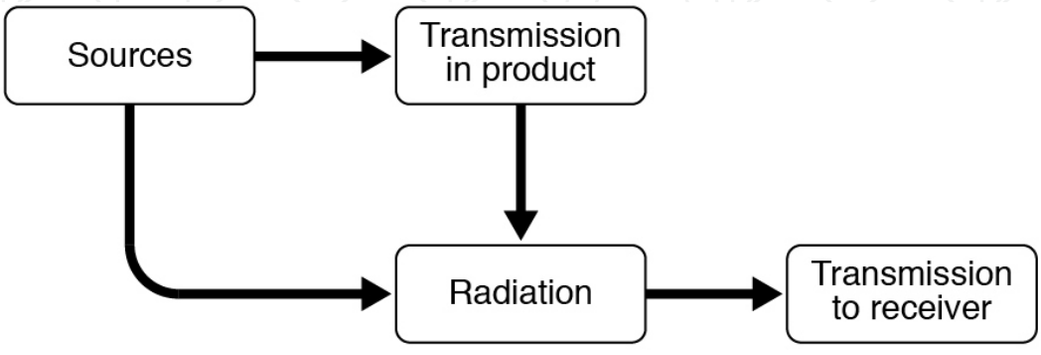


Figure 2. Model for product sound.

The sources of sound are defined as: airborne sound, liquid borne sound and structure borne sound. Gaver (1993) mentioned the events as sound sources, the interaction of material at a location in an environment with a certain impact caused by the power. The power sources could be from outside the product as electricity, water, gas and air. For example electricity is mostly used in domestic appliances or consumer goods such as: coffee maker, dish washer, extractor fan, convection oven, electric drill, shaver, grinder, hairdryer etc. Examples for water could be the tap in the kitchen, water sprinkler for the garden, sprinkler installation as fire protection etc. Gas and air also have good examples in the home such as: stove in the kitchen, airbrushes for decoration etc.

The energy can also be stored in a battery, gas bottle, container or human. This energy can be delivered to the product at the desired moment for a limited time. For example, the water tank (container) of a toilet is used for flushing the toilet bowl after use of the toilet and it is then filled again. The water contains the amount of potential energy that is needed to flush the toilet.

In table 3 (next page) the sound sources with primary excited medium are defined. Type of excitation should be always an activity such as: mechanical, aero dynamical, hydro dynamical etc. The examples are experienced in daily life in a household and a manufacturing plant. Özcan has six product sound categories defined; these are not based on sources but on the experience of the sources. There is always energy stored in the sources or fed from outside the product by the power outlet.

Radiation is the excitation of airborne sound by surfaces and other parts of a product. In water such as: mobility for boats, water bikes, wind surfboard, etc. the radiation of sound is also important. Transmission of sound takes place by means of the transfer of the primary excited medium such as construction, air and liquid. In a product multiple propagation paths may occur depending on the product layout. Construction sound transmission are carried out by the components of the product, but air and liquid sound transmission is carried out by air and liquid -filled cavities or by the mediums air and liquid.

The receiver always experiences the product sound in an environment, but the sound propagates from the product by air. However, the sources are experienced after the transmission in the product and the radiation to the environment. Cooking on a gas stove is nice example because you experience the amount of gas flows that simultaneous burns. Besides you also experience the gas flow as high or low at a certain distance. The gas supply with small pressure and combustion have an interaction with the environment.

Two approaches are possible to create the desired product sound. The first approach may reduce noise, e.g., projector, air conditioning, air hammer etc. The second approach is a product sound design (powerful experience, intensive experience) to be designed; e.g., electric shaver, toothbrush, electric power tool.

Before the desired product sound can be designed, the product must be measured against the sound of an existing product. From a product design, a prototype can be built which can also be measured. Measuring the individual contributions of the parts and components are notified through disassembling (deconstruction) a product, removing part after part.

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Sources	Primary excited medium	Type of excitation	Examples
Air borne sound	Air or another gas	Mechanical	Compressor Refrigerator
		Aero dynamical	Fan Turbulent flow
		Combustion	Exhaust gasses in the exhaust pipe Autogenous welding Gas burner
Liquid borne sound	Liquid	Mechanical	Plunger pump Gear pump
		Hydro dynamical	Turbulence in flow Cavitation
Structure borne sound	Construction	Mechanical	Inertia: unbalanced
		Aero dynamical	Collide: hammering, rolling, stamping, sawing Turbulence gas flow Air spray
		Hydro dynamical	Releasing of whirls Air jet on surface Water heating
		Electro mechanical	Pole attraction Magnetostriction in transformer

Table 3. Defining the sound sources.

3. Intentional product sounds

Intentional sounds are 'intentionally' implemented and are typically produced by means of a loudspeaker or piezo element. They are mostly digital and somewhat musical sounds often used in user interfaces. Intentional sounds can be found in, e.g., domestic appliances (e.g., alarm clocks, mobile phone button beeps, microwave oven finish bells, operating system welcome tunes), automotive (e.g., low fuel warning, unfastened seatbelt alert), public transport (e.g., beeps at check-in points), and healthcare (e.g., heart-rate monitoring). These synthesized or recorded sounds are typically created using music software. The function of intentional sounds is often to alarm or to provide feedback to users.

This section first provides an elaboration on different functions and types of intentional sounds. Then, an overview will be given on commonly used techniques for implementation. A suggested design process for these sounds can be found later in this chapter.

3.1. Functions of intentional sound

Added sounds are regularly used to communicate abstract meanings or to provide information about the result of a process or activity (feedback). For example, when pressing membrane buttons on a microwave oven, the buttons themselves do not make sound. However, a 'beep' sound produced by a built-in piezo element will confirm the user's choice, after which the microwave's platform starts to rotate and produce its typical cyclic sound. This illustrates how as augmentation, intentional sounds are not inherently coupled to either a user's action or a product's functionality (see: consequential sounds). Yet, listeners learn to attribute meaning to added sounds, as they are generally designed to convey certain messages. For example, Edworthy *et al.* (1995) investigated the potential effects of changes in acoustic parameters (e.g., pitch, rhythm) on associated meanings (e.g., controlled, dangerous, steady). This attribution process is highly context-dependent. Consider how the perceived urgency of identical warning sounds may be different depending on whether it indicates a low battery warning of a mobile phone, or a problem with a heart rate monitoring system. See Hoggan *et al.* (2009) for an example on contextual differences in mapping audio parameters to informing signals by user interfaces (i.e., confirmations, errors, progress updates, warnings). Furthermore, product sounds are always part of a larger auditory environment. For example, an intensive care unit consists of a wide range of monitoring equipment. Lacking a standard for their alarm sounds, nurses potentially mistake a 'code red' alarm of one machine for a 'mild' alarm of another machine (Freudenthal *et al.*, 2005, Sanderson *et al.* 2009). Therefore, it is essential to design intentional sounds based on the interactions users (should) have with the product in a given context, and based on how people perceive these sounds.

One can differentiate between discrete and continuous feedback. The button tones of a microwave oven serve as confirmation of a completed action. They give discrete feedback, as they only sound once after a key has been pressed. This is different from continuous monitoring of a process, such as the series of beeps emitted by parking assistants in modern cars. Here, the time between consecutive beeps is inversely related to the distance to the car behind. Therefore, this is also an example of dynamic feedback. On the other hand, the microwave button tones always sound the same, regardless of how the user pushes them. Thus, this type of feedback can be called static. The decisions between discrete vs. continuous and dynamic vs. static feedback have consequences on the implementation of the corresponding sounds, as will be shown later.

3.2. Classes of intentional sound

One can discern between four main classes of intentional sounds: earcons, auditory icons, sonification, and continuous sonic interaction. The examples given so far mainly consisted of beep-like sounds. They are part of a larger class of discrete musical sounds which are called *earcons*. As discussed before, the abstract mapping of earcons must be learned, as there is no

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semantic link between the sounds and the data they represent. Differentiation is commonly found in terms of pitch, rhythm, timbre, spatial location, duration, and tempo (Hoggan *et al.* 2009). A second class of intentional sounds are *auditory icons*. Contrary to earcons, these are natural, everyday sounds, which are described in terms of their sources (e.g., the air flow sound of a fan to represent the state of a steam vent). Due to their semantic link to the things they represent, auditory icons are supposedly easier to learn and remember than earcons (Hearst *et al.* 1997). A third class of intentional sound is *sonification*, which concerns continuous data display. An ongoing awareness of a total system can be created, by including both alarming sounds and reassuring sounds for 'normal' states. Barrass argues that sonification can be used for monitoring an entire system, whereas earcons and auditory icons are better suited for diagnosis of subsystems (Hearst *et al.* 1997). Finally, a fourth class of intentional sounds has emerged. Rather than focusing on system states, *continuous sonic interaction* aims at sonifying expressiveness in human-product-interaction. A study by Rocchesso *et al.* (2009) illustrates how dynamic, continuous sound can influence the way we interact with a range of experimental kitchen appliances.

3.3. Implementation of intentional sounds

Intentional product sounds are typically generated with music software. The type of implementation depends on the classes of intentional sounds. Two main approaches can be discerned: recording and parametric synthesis. In the recording approach, (parts of a) product or environment are recorded, which can be done outdoors with a field recorder, or in an acoustically-treated recording room. The absence of room reverb in the latter condition facilitates editing at a later time. Recordings can be manipulated (e.g., equalization, compression), sliced, and layered to create a more complex sound. The main advantage of using recordings is the ease with which a realistic sound can be obtained. This approach lends itself well to creating auditory icons. However, recordings are not as flexibly manipulated as sounds created with parametric synthesis.

Parametric sound synthesis concerns the creation of sound starting from nothing. This implies that every sound feature deemed important should be included in a model. With such a model, the sound can then be manipulated according to its corresponding parameters. Typical techniques include additive, subtractive, wavetable, amplitude modulation, frequency modulation, and granular synthesis (examples on these techniques can be found in Farnell, 2010). Here, the use of elementary waveforms (i.e., sine, saw tooth, triangle) and/or noise is the common starting point. Parameters usually relate to an acoustical description of the sound (e.g., saw tooth wave and filter cutoff frequencies). Another technique that has gained increased attention over the years is physical modelling. This technique commonly employs mass-spring, dampener, and resonator models that mimic the working principles and construction of, e.g., musical instruments. Consequentially, parameters relate to 'natural' features, such as plucking force, string length, and material thickness. Rocchesso *et al.* (2009) argue that for continuous sonic interaction "the main sound design problem is not that of finding which sound is appropriate for a given gesture. Instead, the main problem is that of finding a sensible fitting of the interaction primitives with the dynamical properties of some

sound models, in terms of specific perceptual effects." Parametric synthesis offers great flexibility, but at the cost of an increased effort to generate realistic, appropriate sounds.

The product sound designer should decide whether the sound will be presented static or dynamic. In the case of static sounds, one may choose to save them as samples to a dedicated piece of memory. The samples can then be played back on-demand. This is often the case with auditory icons and earcons. However, for sonification and continuous sonic interaction, both dynamic by definition, the synthesis model itself will have to be implemented in the chipset of the product. The sound will then be generated and manipulated in real-time, depending on the input of sensors. Note: the implementation of a synthesis model is not always feasible for complex sounds that require CPU processor-intensive models.

Finally, a sound that has been created digitally requires at least a digital-to-analogue convertor, and a loudspeaker or piezo element to be heard. For optimal acoustic efficiency, the resonance frequency of the cavity in which the loudspeaker or piezo element is mounted may require tuning to the frequency content of the envisioned sound.

4. Product sound design process

Aforementioned intentional and consequential sounds can be designed in order to facilitate a certain product experience. The main aim of the sound design process is to facilitate an auditory experience by using product sounds that are complimentary or supportive to the main product experience. For example, the warning signal of a microwave oven could be designed to be 'inviting' or a shaver could be designed to sound 'sporty'. In both examples, the desired auditory experience can only be achieved by forcing changes into the constructive elements of the main product, as sound is a natural consequence of objects/materials in action.

The design of the consequential and intentional sounds undergoes an iterative process (similar to the method suggested by Roozenburg and Eekels, 2003) that runs parallel to the main design process so that communication between different design teams is kept at its highest level of knowledge-exchange. Thus, a product sound design process incorporates four stages (see Figure 3):

1. *sound analysis* within product usage context;
2. *conceptualization* of ideas with sounding sketches;
3. *embodiment* of the concept with working and sounding prototypes;
4. *detailing* of the product for manufacturing with sounds fine-tuned to their purpose.

In light of the four-stage sound design process, it is often the case that sound design process starts with the main design brief, in which special attention may have been paid specifically to sound. However, usually the main design concept suggested in the brief can be taken as the basis for sound design.

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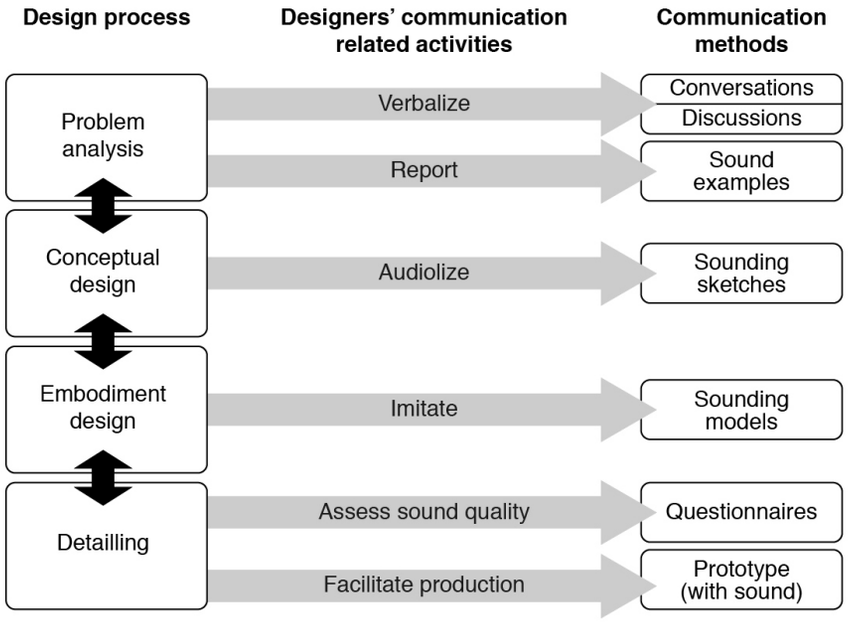


Figure 3. Methods for product sound design -related activities (adapted from: Özcan & van Egmond (2008))

4.1. Stage 1: Sound analysis

The sound analyses stage starts by first determining when and how the product emits sound and how the sound is incorporated into the human-product interaction. Therefore, observational research with high-definition audio-visual recordings is necessary to place the sound in context with the user in an environment natural to human-product interactions. In such observations, the following issues should be considered or paid attention to:

- acoustic effect of environment on the sound,
- other environmental/product-related sounds that could mask the sound in question,
- interaction of the product with the user and environment,
- facial expressions of users for detecting unpleasant or unwanted sounds,
- stages of product use and occurrence of sound in any given stage,
- duration of the product use and exposure to sound,
- impact of sound on product usability.

After tackling these issues and making a map of auditory experience within context, dry recordings of the product sound in a studio environment can be taken. Both dry and environmental sound recordings can be further analysed in terms of acoustic content of the sounds (e.g., Spectrograms, Bark scales) and their basic relevance to psychoacoustics. Subsequently, a comparison can be graphically made between a product sound occurring in a natural environment and the actual sound of the product without any environmental effects.

The acoustical analysis of sounds is also used to pinpoint acoustic regions that can cause sensory discomfort and locate the region or part where the problems with sound occur. Thus, the sound analyses stage continues by analysing the effect of the assembly parts of the product on the product sound. This is carried out by disassembly of the product in a by step-by-step fashion and recording at each stage of disassembly until the last sound-producing component is left. Again, acoustical and psychoacoustic analyses are required for each recorded sound. This is a crucial stage in product sound design that aims at determining which existing component of the product is problematic and can be replaced.

As exemplified above, the sound analysis stage is based on many iterative processes that involve observations and analyses into human-product interaction within context, the acoustical content of the sound, and physical construction of the product. Such analyses lead to understanding the conceptual and functional role of sound in human-product interaction.

4.2. Stage 2: Conceptualization

Once the conceptual and functional problems with product sounds are identified during the sound analysis phase, designers can proceed with conceptualizing the to-be-designed new product sounds. The conceptualizing should incorporate the desired product experience (as defined in the product brief) as a reference but focus on the sound-specific relevance to the desired experience. For example, if a shaver is being designed to be *sporty*, the sound does not necessarily have to refer to this concept directly. Semantic associations (i.e., sub-concepts) of *sporty* (e.g., *powerful, dynamic, energetic*) applied on the shaver sound would be also satisfactory as a contribution to the overall product experience.

Therefore, at this stage, it is important first to define the semantic associations of the desired product experience in order to determine what underlying concept could be taken further for sound design. Such conceptual analysis can be made with the help of a couple of methods (Özcan & Sonneveld, 2010). Mindmapping, bodily explorations, and acting out are complimentary methods that help to deconstruct the meaning of a desired experience. With bodily explorations, designers try to put themselves in a, e.g., *sporty* mood and determine situations when one feels sporty (e.g., jogging, playing tennis). They internally observe what happens in their body if they are sporty and further check their emotional state to determine how pleasant, aroused, or powerful they feel. With acting out, designers physically act out, e.g., *sporty* by moving their bodily parts, vocalizing sounds accordingly, and interacting with other objects. This method is important to determine the physical and temporal properties of the desired experience. Once such explorations into meaning deconstruction are complete, designers can summarize their experiences with the help of a mind map (a.k.a. knowledge map). The purpose of the mindmap is to systematically unravel the meaning of a desired experience, which is an abstract term, and relate it to physical properties of objects/interactions/sounds, which are concrete entities. Furthermore, mindmaps often help designers to determine metaphors which may be useful for the application of the concept. As a result, a concept supporting the desired product experience can be taken further for sound sketching.

Once a concept is selected, a next step is to audiolize this concept with sound sketching. The ultimate goal of sound sketching is to find auditory links that may underlie the selected concept

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(and the desired experience, directly or indirectly). Sound sketching can be done via tinkering with objects, vocalizations of sounds, and/or using a sound sketching tool (e.g., PSST! Product Sound Sketching Tool). With tinkering, designers are encouraged to find objects that can express the desired auditory expression when in interaction with other objects. It is important here how designers tackle the objects, with what actions and movements. Tinkering is all about creating sounds with ordinary daily objects. With vocalization, designers can vocally imitate the sound with auditory expressions of the desired experience. For example, having learnt during the prior bodily/physical explorations that a *sporty* sound should be *energetic*, *dynamic*, *determined*, etc., designers can vocalize an engine sound with such auditory expressions. Finally, if designers have access, they can sketch sounds with a specially designed interactive tool such as PSST! (Jansen, Özcan, & van Egmond, 2011). PSST! allows designers to create digital sounds with previously recorded samples by manipulating the timbre, sound intensity, and pitch. PSST! is more suitable for consequential sounds.

The conceptualization phase is complete once the desired auditory expression has been determined. The sound sketches can be further used as a guide for the prototyping of the product with the desired auditory expression.

4.3. Stage 3: Embodiment

In the design and construction of the products, the embodiment phase is the first moment when designers encounter sounds emitting from the newly designed product. The embodiment phase for sound design concerns the physical product parts that need to be altered/replaced in order to create the desired auditory experience. Therefore, the problematic parts encountered in the analysis stage will be tackled at the embodiment stage. One activity that is essential to this stage is the prototyping. Designers need to partially prototype the product in order to observe the occurring sound and verify its fit with the desired auditory features and experience.

Similar to the sound analyses stage, each occurring sound needs to be acoustically analysed. The same methods of sound recording and analysis such as used in the analyse phase can be adopted here. However, the observations and conclusions should be tackled around the desired auditory experience.

Tools and methods used for the embodiment design of sounds depend on the type of sound. Intentional sound design and application require more digital techniques to construct the sound and consequential sound design and application would require more analogue techniques to construct the product, hence the sound.

4.3.1. Intentional sounds

Intentional sounds are by nature music-like sounds, thus they can be created from scratch with the help of a musical instrument or a computer with proper sound editing tools (e.g., Garage band, Audacity). Timbre, temporal structure, and length are some factors that need to be considered when designing intentional sounds. The intentional sounds are already described in chapter 3.

4.3.2. Consequential sounds

For example, if a food chopper is producing an unwanted fluctuating sound and it has been found that the mill that turns the blade was found vertically tilted due to bad assembly; then, a better construction that stabilizes the mill could be proposed. In another example, the working principles of a coffee machine could be altered by… in order to create the feeling of efficiency and comfort. Furthermore, once the main assembly of the product is finished and a rough sound can be produced, it is possible that old-fashioned techniques of noise closures and dampening could be employed before the casing is designed and assembled.

The embodiment design phase is complete once the guidelines for the final prototype are achieved. It should be kept in mind that the product sound occurring at the prototyping stage may be different to the sound of the final product. Thus, the embodiment sound design phase consists of iterative stages of creating sounding models, (dis)assembling, and testing with the aim of achieving the desired experience with the final product. The tests involved here range from acoustical measurement and analysis of the sound via a computer to see whether the product sound fits the technical requirements, or cognitive evaluation of sound with potential users to ensure that the occurring sound semantically fits the desired experience. Moreover, with the sounding models, desired interaction with the product can be enabled and observed. This could be done with the help of potential users acting out towards the product and the design team, enabling the interaction with the wizard-of-Oz techniques.

4.4. Stage 4: Detailing

In the detailing phase, fine tuning of the product sound takes place. At this stage, the final prototype is built and the product to-be-produced takes its final shape. A more realistic sound is expected as an outcome. More extensive user research takes place with semantic differentials and observational studies. Collected data should yield more accurate results and conclusions regarding the desired experience and interaction. It is possible that the occurring sound still needs further adjustments. At the detailing stage, there will be room for further noise closure and dampening activities that roughly concern the outer shell of the product. At the end of detailing, the product should be ready for manufacturing.

5. Product sound designer

Sound design activities exemplified above are multi-disciplinary by nature and relate to three indispensable disciplines: *acoustics*, *engineering*, and *psychology*. Each of these disciplines contributes equally to the sound design process and a sound designer needs to have insights into each of them. Figure 4 demonstrates how knowledge from these disciplines feeds the sound design process. In the following paragraphs we will explain the individual contribution of these different fields of expertise and create the profile of a sound designer.

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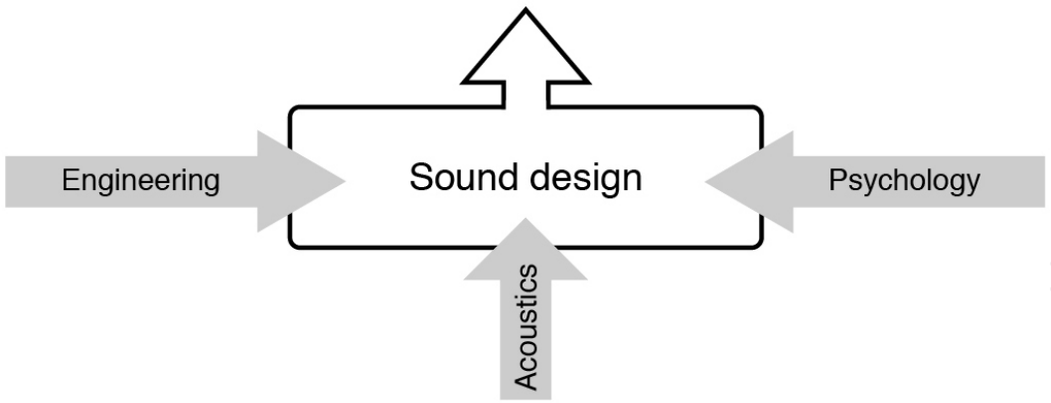


Figure 4. Main disciplines contributing to product sound design activity (adapted from: Özcan & van Egmond (2008)).

5.1. Acoustics

Acoustics is the science that tackles sound phenomena. The field of acoustics is concerned with basic physical principles related to sound propagation and mathematical and physical models of sound measurement. Therefore, the topics of interest for the field of acoustics are the medium in and through which sound travels, reflecting and vibrating surfaces, speed of sound, and other physical characteristics of sound such as sound pressure, wavelength and frequency.

Sound is a result of the energy release caused by objects in action. Although the physical quality of the sound is determined by the sound source and action, *acoustics* does not necessarily investigate the source per se. The physical properties of the source (e.g., the interacting materials, weight, size, and geometry of the objects) are of interest for acousticians. Furthermore, sound propagates over time because it is the result of time-dependent dynamic events. That is, the physical character (i.e., spectral-temporal composition) of a sound changes over time depending on the type of actions and sound sources. For example, a piano produces a harmonically and temporally structured sound. A lady epilator produces a noisy sound because it contains multiple sound-producing events, each creating different harmonic partials and occurring at different time frames, causing temporal irregularity.

It is essential to understand the acoustic nature of the sound event when designing product sounds. Acoustic analysis of the sound can be first done during the problem analysis phase and can recursively occur until the problem has been defined. The field of acoustics provides tools and methods to analyse and simulate sound. Basic terms used for sound characteristics comprise of 'frequency' (variation rate in the air pressure), 'decibels' (sound intensity), and 'amplitude' (sound pressure). A spectrogram visualizes the frequency content of a sound and the intensity variations in time. Furthermore, a sound wave represents the temporal tendency of sound propagation and the sound pressure over time. It is possible to visually analyse the spectral-temporal composition of a sound event and precisely pinpoint the acoustical consequences of certain events. Moreover, various sound modelling techniques have been developed in the field of acoustics. Simulating sounding objects that are perceptually convincing has been possible thanks to the available computer technology (Cook, 2002; Pedersini, Sarti,

& Tubara, 2000; Petrausch, Escolano, & Rabenstein, 2005; Rocchesso, Bresin, & Fernstrom, 2003). Furthermore, sound simulation can also be necessary to test upfront the perceptual effects of the desired sound.

5.2. Engineering

Engineering is the discipline through which abstract scientific knowledge takes on an applied nature. For the design of product sounds, three main branches of engineering provide knowledge: mechanical engineering, electric-electronics engineering, and material engineering. These relevant fields deal with sound indirectly and rather focus on manipulative (i.e., constructible) aspects of products. Various product parts, mechanisms, lay-out, materials, interactions, and working principles can all be engineered depending on the design requirements of the product and its sound.

In product engineering, functionality of the product should be the main focus. Thus, suggested alterations for the improvement of the product sound can only be carried out if the functionality of the product or product parts are kept intact. Engineers should have satisfactory knowledge on physics and mathematics, and they are able to calculate the energy release as sound or as vibration. Furthermore, the discipline of engineering provides various tools and methods to embody conceptual ideas and solutions to problems. Engineers and designers are well-supported on modelling, testing, and prototyping (Cross, 2000; Hubka & Eder, 1988; Roozenburg & Eekels, 1995). Similar tools and methods could be used for implementing product sounds as well.

5.3. Psychology

Sound design is not limited to finding technical solutions for a problem. The aforementioned disciplines deal with the physical aspect of sound and the object causing the sound (i.e., product). However, product sounds, just like other environmental sounds, have psychological correlates which may be on a semantic level or an emotional level (von Bismarck, 1974; Kendall & Carterette, 1995; van Egmond, 2004).

Listeners main reaction to any sound is to interpret it with their vocabulary of previous events. Such interpretations often refer to the source of the sound and the action causing the sound, such as a hairdryer blowing air Marcell, Borella, Greene, Kerr, & Rogers, 2000). Listeners are able to follow the changes in the spectral-temporal structure of the sound and perceive it as auditory events or sometimes as auditory objects (Kubovy & van Valkenburg, 2004; Yost, 1990). In the absence of image, just by hearing listeners can describe the material, size, and shape of the sound (Hermes, 1998; Lakatos, McAdams, & Causse, 1997).

For product sounds the conceptual network consists of associations on different levels (Özcan van Egmond, 2012). Source and action descriptions occur the most, followed by locations in which products are used the most (e.g., bathroom, kitchen), basic emotions (e.g., pleasant-unpleasant), psychoacoustical judgments (e.g., sharp, loud, rough). In addition, source properties can also be identified (e.g., interacting materials or sizes of the products). Furthermore, product sound descriptions could also refer to rather abstract concepts such as hygiene

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(for the sound of washing machine), wake-up call (for the sound of the alarm clock), and danger (for a warning buzzer).

These conceptual associations of sound indicate that a fit of the sound to the product or with the environment in which the sound occurs is judged. Therefore, a design team cannot overlook the cognitive and emotional consequences of the sound. In various stages of design, user input needs to be carefully considered. Therefore, questionnaires that are aimed at measuring the psychological and cognitive effect of sound could be used.

5.4. Hybrid disciplines: Psycho-acoustics and musicology

Above we discussed the major disciplines contributing to sound design. However, some hybrid disciplines also contribute such as psycho-acoustics and musicology. The field of psychoaoustics deals with the basic psychological reactions to the acoustic event. Sharpness (high frequency content), roughness (fluctuation speed of the frequency and amplitude modulation), loudness (sound intensity), and tonalness (amount of noise in a sound) are the main parameters used to observe the psycho-acoustical reaction of listeners. Although these parameters are supposed to be subjective, a general conclusion has been made in the past regarding the threshold and limits of human sensation to sounds. Therefore, psycho-acoustical algorithms have been presented to measure the above-mentioned perceived characters of sound (Zwicker & Fastl, 1990). These algorithms are used to measure the sounds perceptual quality and predict listeners tolerance to sounds. Thus, they are predictive of sensory pleasantness or unpleasantness.

Designers can design alarm-like synthesized sounds if they have knowledge and practical experience in the field of musicology, as composing music that requires knowledge on theories about musical structures and compositions and tools to create harmonic and rhythmic sounds.

5.5. Responsibilities of a product designer

A product sound designer should have knowledge and skills on three major disciplines (engineering, acoustics, and psycho-acoustics) and also on hybrid disciplines such as musicology and psycho-acoustics (see Figure 5).

A product sound designer is primarily an engineer that is able to manipulate the product lay-out and is skilful in applying physical and mathematical knowledge in order to analyse and to model the product lay-out while considering the consequences in terms of sound.

However, interpreting the physics of sound per se should also be one of the major roles of such an engineer. Skills in acoustic analyses and ability to simulate sound are necessary. Furthermore, a sound designer should be able to link the structural properties of a sound to its acoustical composition. In addition, musical knowledge on how to compose synthesized sounds is required in the case of the intentional sounds.

Furthermore, the psychological correlates of the product sound should also be considered when an engineer is tackling the physical aspects of sound and the product as a sound source. Ultimately, the product sound designer has the last word when judging whether the sound

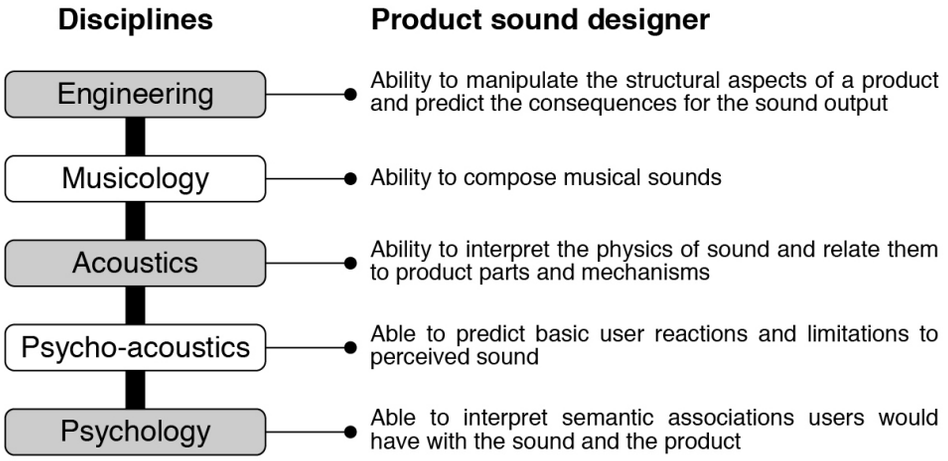


Figure 5. Professional domains of a sound designer (adapted from: Özcan & van Egmond (2008)).

fits the desired experience and the interaction within the context of use. Knowledge on psycho-acoustical analyses is required to predict the first user reactions only to sound. Later, semantic analyses need to be conducted with potential users to make sure the sound design is complete and appropriate to the product.

6. Product sound design course

Product Sound Design is an elective course of the Master of Industrial Design Engineering Education at Delft University of Technology. In product sound design we distinguish two main types of sounds: Intentional sounds and Consequential sounds. The two types of sounds are addressed to the second half year - in the first quarter intentional sound and in the second quarter consequential sound. The students involved are working in project teams of two or three students. The elective consists of a project with few lectures to support the project. The final results should be presented to all course members and stakeholders in a colloquium. The presentation takes approximately 25 minutes with 5 to 10 minutes for questions and discussion. The project is graded on the deliverables: presentation, and report. For the projects, domestic appliances are chosen such as: kids alarm, public public transport card check in and check out, electrical toothbrush, choppers in different versions, shavers, etc..

6.1 Intentional sound project

The intentional sound project approaches the design of these sounds from an interaction perspective. These sounds are synthesized or recorded and are often more musical or speech-like. Therefore, the sounds are created by use of music software. The function of sounds is often to alarm or to provide feedback to users. The project focuses on perception and re-design of these sounds from n interaction point of view . It is essential that these sounds are designed on the bases on the interactions, otherwise improper sounds will result.

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6.2 Consequential sound project

The consequential sound project focuses on the sounds radiated by domestic appliances, and are a consequence of their operating and construction. The students will analyse the sounds in the physical, perceptual, and emotional domain and try to relate these findings to the engineering parts of the product. A product should be disassembled and sound recordings will be made of different parts in order to obtain insight in the contribution of these different parts to the sound. The findings resulting from the analyses in the physical, perceptual, and emotional domain are used to redesign new parts or different working principles.

6.3 The study goals

The study goals provide a basis for the self-development of a designer in the field of product sound design. The goals are:

- To be able to implement their findings from the analyses in the physical, perceptual, and emotional domain into an adapted product design,
- To learn how sound is produced in products and experienced by people,
- To learn basic principles of signal analysis (related to sound),
- To learn the effect of tolerances on the performance of the appliances and its sound production,
- To learn the relationship between product quality and sound quality.

The students get 6 ects (European credit transfer system) for this elective course. This means that they have to invest 168 study hours to come to new ideas and realize them in an adapted or innovative product sound design. The valuable results of three years since the elective started were used to develop further on the elective product sound design.

First of all, because the education method of this elective was very successful it will be upheld. The students are working in project teams because of the complexity of the topic. The frontal lectures are limited to project planning and organization, and to an introduction into the basics of product sound design. Sound recording is explained as among which: use of software, lab set-up, and how to record. Most recordings will be carried out in the Audio Lab, but if the project requires recordings can be made at a specific location (e.g. public transport card project). The coaching of the teams is on the initiative of the students which stimulates them in their search for creative and innovative solutions. At specific moments during the project, teams have to explain the project progress. During these moments coaches discuss the progress and results and give advice to go into a certain direction when necessary The results of a project are presented in a colloquium and a written report.

6.4. The case: Toothbrush

We use a student project of a toothbrush as an example. The team measured the sound under load, shown in the lab setup in figure 6. This laboratory setup is easily adaptable to record the

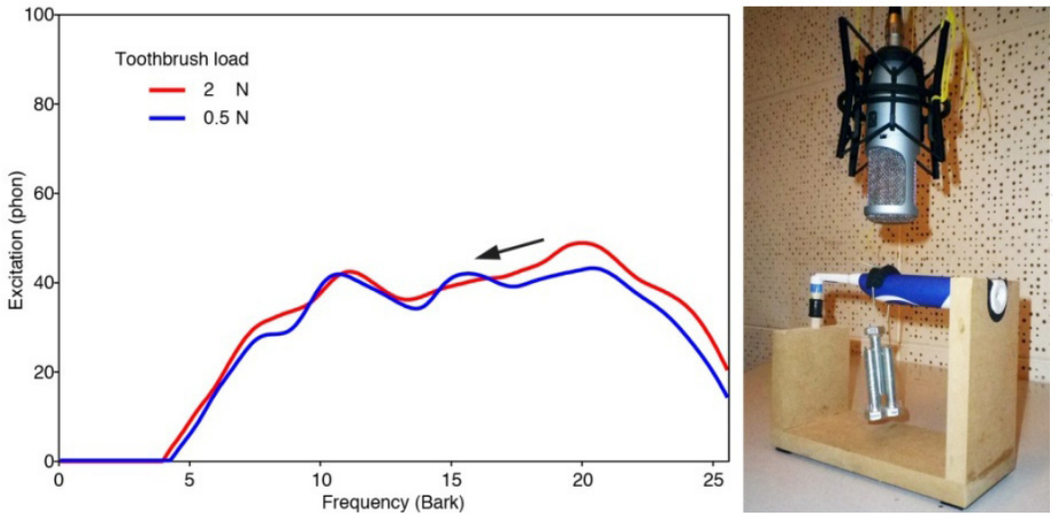


Figure 6. Laboratory setup and Barks analysis for the maximum and minimum load on the toothbrush. The load will be applied by hanging bolts on the toothbrush.

sound of the toothbrush under different loads. A sound level meter is used to obtain the loudness level in decibels. The recordings will be analysed to get insight into the sound effects at different power loads. The brush force for brushing teeth effectively lies between a maximum of 2N and minimum of 0.5 N in normal use.

The maximum load applied to the toothbrush is determined by the operation of the toothbrush at the boundary of the function in this case. The minimum load of the toothbrush is determined by its own weight. Figure 6 shows the graph of 2N and 0.5N loads - the influence of load on the toothbrush can be observed on the Bark scale. A peak is observed at 20 Barks for a load of 0.5N. It moves to a lower frequency domain of 15 Barks when the maximum load is reached.

The disassembly of the toothbrush is carried out in order to analyse the recordings of the parts contributing to the sound. In figure 7 the inside organization of the toothbrush is shown.

Disassembling of the toothbrush from complete product (situation black) to only the electromotor (situation brown) the recordings in barks in figure 8. The different graphs of disassembling the product are given in different colours. With a decrease of number of parts (disassemble step after step), the sound will gradually cut down.

The main axel (situation blue) is the main cause in the irritating rattling noise. When removed (situation green), there is a big decrease in the peak around 20 barks and a lowering of 6dB in volume. In the last stage of disassembly (situation brown), only the motor is active, that results in a sound of 45 dB. Gearing parts are assembled on the motor; this will increase the resistance that contributes to a louder sound, especially in the lower-frequency domain.

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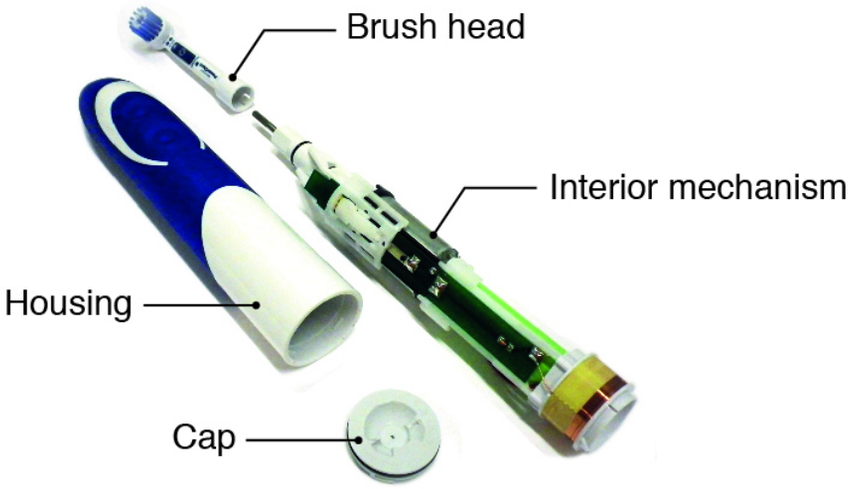


Figure 7. Inside image of the toothbrush.

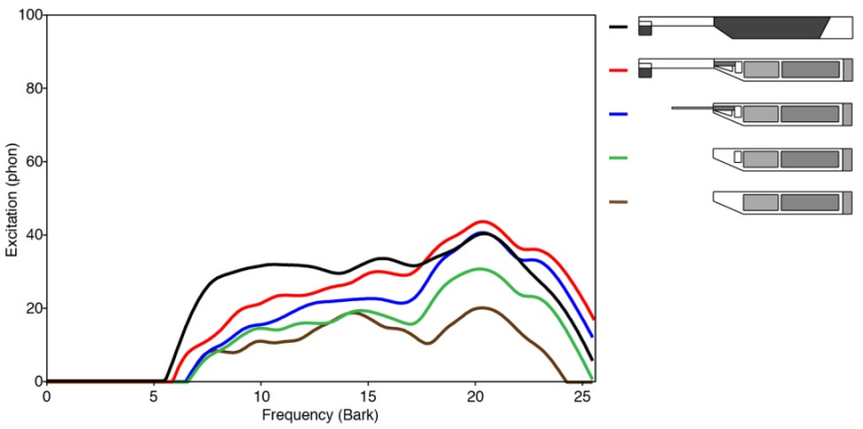


Figure 8. Barks analysis on the complete disassembly of the toothbrush.

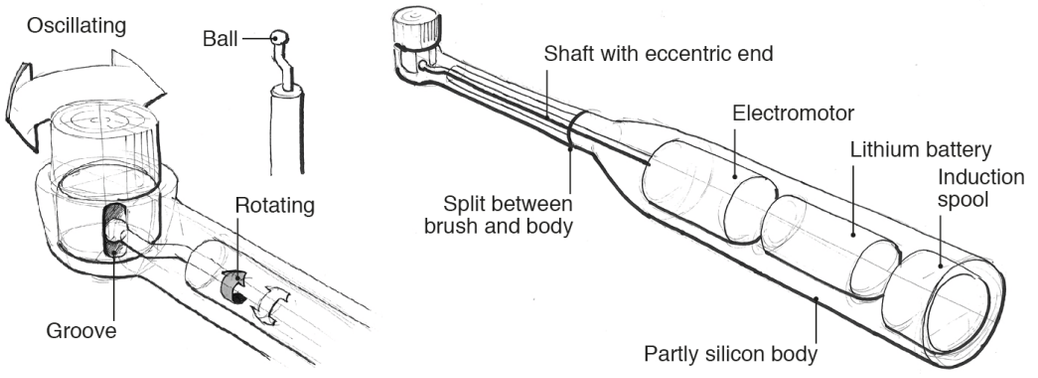


Figure 9. Sketches of the redesign - in this case the working principle is changed.

In final stage, hand sketching is used to express the solution by means of the working principle. Sketching is a handy tool for the designer to visualize the working principle, product ideas, and parts quickly on paper. The sketches show how parts may be produced and assembled. However, implementing it in a product is often not feasible, therefore the intended sound cannot be measured. The toothbrush changes are based on sketching because making a prototype with rapid prototyping could bring you far away from the final solution because the replacement material has never the same sound property. In figure 9 sketches of a redesign are shown.

7. Discussion and conclusion

The two types of product sound need their own design process. Consequential sounds are the result of the product layout. However, the component choice, shape, material and manufacturing are the main parameters that determine the consequential sound. For a new innovative product, sound recordings of different components will be made and mastered into a future product sound (Van Egmond, 2008). In this situation, the product sound will rely on the experience of the product sound designer . In future, this experience should be replaced by a theoretical framework based on research on the following parameters: material, accuracy of parts, the tolerance of parts, how the parts are connected, power transport, size, geometric, speed, and assembly tolerances.

Although consequential sounds are restricted in degrees of freedom by the design and embodiment of the product, the design of intentional sounds has an unlimited number of degrees of freedom due to the fact that they can be designed from scratch. This is one of the reasons that many feedback and alarm signals are badly designed, because no limiting constraints are imposed. If one considers the design of intentional sounds as a form of interaction design, the interaction can impose the constraints on the design of the sounds. Consequently, the sounds will “fit” their function better. Knowledge from interaction design, psychoacoustics, audio engineering and music perception will form the theoretical basis of the design of these sounds.

It can be concluded that Product Sound Design should be a discipline within the domain design. Especially, the physical and psychological aspects should be mapped onto each other. The product sound designer has to learn from a variety of disciplines, from design to engineering and from acoustics to music perception. The course in product sound design is a good basis for further self-development of young designers. It enables opportunities for students under supervision of their lecturers to develop a systematic approach for product sound design. Hopefully, this will lead to more knowledge and appreciation of the way sound contributes to the overall product experience.

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