Towards a Design for Acoustics (DFAc) Methodology

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Handling of acoustic properties of products are of increasing relevance in product development. Compared to other properties like weight or manufactorability, acoustics presents a complex property relevant in the use phase of a product and affected by the actual operation conditions. In order to support determination, evaluation and optimization of acoustic properties in early design stages in this contribution fundamentals for a Design for Acoustic methodology are outlined. Therefore, basic elements of DFX methodologies and the evolution of the Design for Manufacture methodology are described. Against this background premises and fields of research are defined to establish a Design for Acoustics methodology.

Die akustischen Eigenschaften gewinnen in der Produktentwicklung zunehmend an Bedeutung. Im Vergleich zu anderen Eigenschaften wie Gewicht oder Herstellbarkeit sind diese Eigenschaften komplex und insbesondere in der Nutzungsphase eines Produkts relevant. Gleichzeitig werden die Eigenschaften durch die tatsächlichen Betriebsbedingungen beeinflusst. Um die Ermittlung, Bewertung und Optimierung akustischer Eigenschaften in frühen Entwurfsphasen zu unterstützen, werden in diesem Beitrag Grundlagen für eine Design for Acoustics Methodik skizziert. Zunächst werden grundlegende Elemente von DFX Methodiken und die Entwicklung der Design-for-Manufacturing Methodik beschrieben. Ausgehend hiervon werden Prämissen und Forschungsfelder definiert, um eine Design for Acoustics Methodik zu etablieren.

Introduction

Discomforts of noise in our environment are frequently associated with insufficient design of products and systems. Despite the increasing relevance of acoustic properties, designers are challenged since they have to consider and fulfil other product properties like reliability, costs or weight in the product development (PD) process. This challenge is frequently caused by physical conflicts hindering to fulfil all product properties at the same time and the different product models needed to represent and evaluate the properties. Approaches of low noise design (Lärmarmes Konstruieren) /1, 2/ support designers by providing measures to reduce sound stimulation, transmission, and radiation. In literature different methods and tools to facilitate identification, evaluation, and modification of acoustics properties within the PD process can be found. Aside from experimental and numerical methods, the importance of expert knowledge is highlighted, in particular to support decision-making early design stages e.g. /3/. With regard to design practice there are frequently challenges to meet acoustic requirements and fulfil additional required properties like weight but also to be efficient with regard to engineering time. In this contribution challenges of handling acoustic properties are discussed from an engineering design perspective. Fundamentals and research of Design for X methodologies are introduced and fields of research towards a Design for Acoustic (DFAc) methodology are discussed.

Acoustic Properties as Complex Product Properties

Following the design theory of Weber, properties describe the behaviour of a product like weight, safety, reliability or manufacturability /4/. From the designers point of view these properties cannot be influenced directly but have to be determined indirectly by characteristics like dimensions, material or the structure of a design solution. Acoustic has to be seen as a complex product property for two reasons. First there is not only one property characterising the acoustic behaviour. The perceived sound of a product is for instance specified by the radiated airborne sound characterised by sound pressure and frequency. Second, the airborne sound radiated by a product depends the stimulating forces, the transmission behaviour of the product itself and its radiation. Focussing on the transmission and radiation of the product there are various properties used to describe the acoustic like damping, insulation or eigenfrequencies and eigenmodes. Compared to other product properties like weight or manufacturability it becomes clear that determining, evaluating and optimizing the acoustic of a product is challenging due to the following reasons:

- Acoustic properties have to be evaluated for assemblies considering different (changing) stimulating forces (differing spectrum and stimulation sites) and transfer path within the product. Thus, acoustic properties are strongly depending on the structure of a system.
- Acoustic properties are mainly relevant in the products use phase and highly depend on the environment and operation conditions of the system. Thus, acoustic properties have to be evaluated for different operating states.
- Acoustic properties are based on the dynamic behaviour of mechanical structures that can hardly be represent by established product models in early design stages.

Scope and Structure of this Contribution

Based on the increasing relevance of acoustics and challenges outlined before, this contribution aims at fostering the integration of acoustic properties as central product properties within the design process – a Design for Acoustics (DFAc) methodology. To originate a DFAc methodology, core elements of the Design for X (DFX) theory are introduced and challenges of integrating DFX approaches into a design process and organisations are discussed in section 2. In section 3 existing approaches to analyse and evaluate acoustic properties are described as well as limitations from an engineering design perspective are introduced. Based on the elements of DFX methodologies, in section 4 fields of research towards a DFAc methodology are highlighted. Section 5 concludes the contribution by a discussion and outlook on further research.

Design for X Methodologies

Design for X means to fit a product to certain life cycle phases or to focus upon certain properties like acoustics /5/. Thus, there are two meanings: the ‘X’ represents a product property (e.g. cost, quality, reliability, etc.) or a life phase like planning, production, use or recycling. While cost elements occur in all life phases, other properties like reliability or assembly lead time are only relevant for a single life phase /6/.

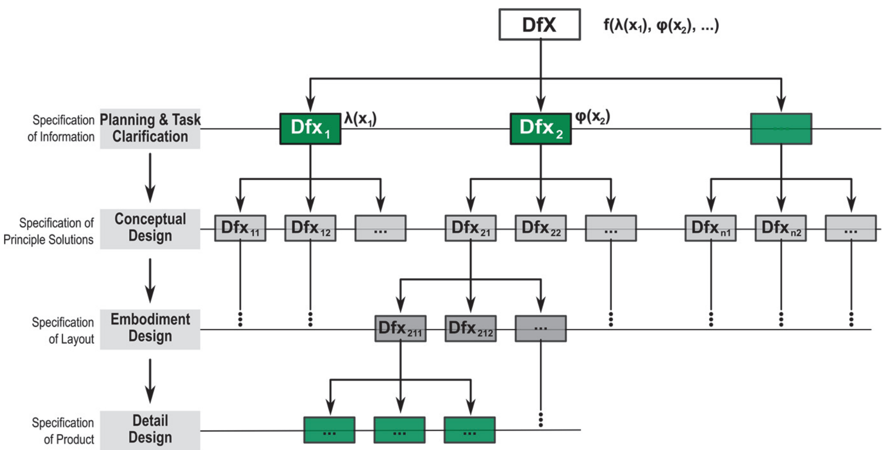

Figure 1: *Correlations between design stages and different Design for X stages based on /7/.*

DFX guidelines used to support designers represent knowledge /8/ and support achieving as many required properties of the product and the connected processes as possible during the PD process /7/. The analysis of information needed from the designer’s viewpoint in different design stages indicates the strong dependency between the different natures of DFX guidelines, see Figure 1. While in early design stages strategic decisions are required and supported by generic guidelines, in later phases more concrete and detailed design guidelines are needed to support e.g. embodiment design or optimization of mechanical structures /7/. Generic demands for low effort on a high level, for example can be realized by low effort in development, material costs or production on a strategic level (planning phase). For each of these fields specific principles provide measures like low running costs (production). Guidelines from the field of design for manufacture (DFM) are needed to support the design of single assemblies or components in the design stages of conceptualisation and embodiment. This highlights the different nature of DFX approaches needed to address the requirements of the specific design stages. On each level DFX methodologies comprise a number of basic elements introduced in the following section and Figure 2.

Basic Elements of DFX Methodologies

DFX methodologies have been extensively researched as a core topic of engineering design /9/. Andreasen & Mortensen /10/ define seven elements indicating the fundamentals and fields of actions to be addressed by DFX methodologies, see Figure 2. These basic elements and their interactions have to be considered when developing DFX methodologies or single tools to support designers.

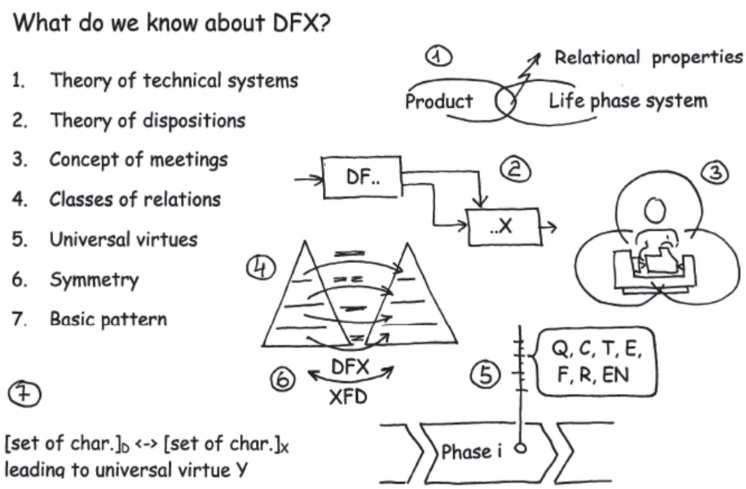

Figure 2: *Basic elements of Design for X Methodologies, taken from Andreasen & Mortensen /10/.*

The *theory of technical systems* /8/ serves as a basis to identify properties of products and design activities and determine relations between the product and its life phases. As a theoretical foundation it has to be recognised for every type of system and product. The *theory of dispositions /11/* clarifies how the design activity influences nature and efficiency of the following design and realisation activities. It highlights the causality and hierarchy of decisions made in the different design stages, see Figure 2. The *concept of meetings* /6/ points out that properties arise and are relevant in a specific activity, in which the product, a certain product life system and operators are acting. Following this concept properties always have a relational character. For instance manufacture costs are rational properties, depending upon the design and a number of (automated) operations in the production system /6/. The element *classes of relations* highlights that in DFX methodologies the product as well as the different life cycle systems have to be seen as hierarchical systems. Relations, therefore, have to be considered on different levels. Focussing the manufacturing area, there are relations between the product and the production system on the levels of product structure vs. production layout, product modules vs. production cells, and components vs. manufacturing processes */6/*. The concept of *universal virtues* provides important classes of properties like quality, cost, time or flexibility to characterise the goodness of a design activity in the PD process /11/. It implements the view on the PD process into DFX methodologies. At the same time this DFX-element highlights the trade-off to be made in a design activity regarding the modelling effort and rigour of property evaluation. The *symmetry* highlights the integration of different responsibilities within the product generation process. With regard to DFM and DFA on the one hand designers have to provide products to good manufacture and assembly, on the other hand manufacture have to offer good processes and assemblies mature for reliable and good products /6/. The most common DFX-element are *basic pattern* identified by practitioners and researchers, based on past designs and for instance production processes and technilogies. As design principles and rules /12/ these patterns are used to support designers for structural definition of the system (high level) as well as specific component and process aspects (low level), see Figure 1.

What to Learn From Design for Manufacture (DFM)?

The analysis of the evolution of DFM gives insights on different approaches for its integration and use in PD. Andreasen et al. /6/ describe four steps of integration, that are derived from the technological evolution in engineering design and production, see Table 1.

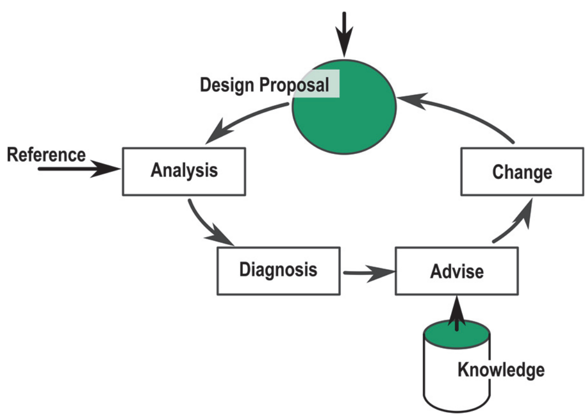

Figure 3: *Integration of Design for Manufacture Tools to Support Synthesis of the Product Solutions in a Corrective Cycle, based on /6/.*

Core object of the first integration step was to equip design engineers with knowledge about the production methods by giving advices like “correct/ incorrect” design. Due to an increasing number of production technologies in the second step, integration of DFM was based on up front specifications, detailed design procedures and standardisation of designs /6/. The third integration step established DFM as team work and addressed the needs of extensive cooperation of design and manufacturing. Integration and scope of DFM activities were supported by models of integrated PD /9/.

Figure 3 presents how DFM tools in this step are used to aid the synthesis of the product in a corrective cycle. Computer integration has been the focus of the fourth step aiming at bringing DFM methodology, knowledge and best practice into computer systems. Here different approaches were pursued to link DFM principles and advises to the actual task of the designer: 1) Diagnostics based automatic analysis of design proposals to give advices for suitable adaptions; 2) Visualisation and knowledge support for life cycle consequences of design decisions; 3) Guidance through a sequence of detailed design steps, where each step is followed by inspection questions and advices. Independent from the approach Meerkamm & Koch /13/ point out that many DFM tools become islands since the software uses its own models of the design. In Table 1 the steps described for the evolution of the DFM methodology are summarised, denoting their focus and main challenges.

Table 1: *Steps for the evolution of the DFM methodology*

Step	Focus	Challenges
Well-known Relations & Solutions	Identify & establish knowledge about production methods	Low number of production methods increases and change over time
Up Front Specification & Design Procedure	Integrate restrictions into design; define procedures & standards	In-depth knowledge about (changing) production methods low cooperation level
Stakeholder Cooperation & Corrective Cycle	Integrate activities of design and production system planning	Identification of dependencies between activities and use of robust information as well as shared models
Computer Integration	Integrate DFM methodologies, knowledge, best practices into software systems	Specific model of the product increase overall effort in design process

The ordering of the steps given in Table 1 is based on the evolution of DFM over time and at the same time includes insights and causations to be considered when establishing a DFAc methodology.

Approaches to Analyse and Evaluate Acoustics

There are different methods to analyse and evaluate acoustic properties during PD. Approaches form Low Noise Design support PD processes by assisting to define acoustic relevant requirements, compare design solutions with regard to acoustic properties or acoustic analysis for prototypes /3/. Methods in the field of machine acoustics are focussing on exact calculation or emulation of the acoustic behaviour of products using numeric methods. Existing approaches in these fields are analysed and compared form an engineering design perspective, placing the used product models and considered product properties in the PD process.

Low Noise Design (Lärmarmes Konstruieren)

Acoustic product properties can be affected in each design stage. Dietz & Gummersbach /1/ provide a comprehensive list of design guidelines and examples to affect acoustic properties distinguishing the origin of vibrations (source of excitation), the path between the excitation and emission and the surface (source of emission) as main design elements. Most of the guidelines have to be allocated to the embodiment phase, since quantitative product characteristics (material, dimensions, etc.) are needed. In order to evaluate acoustic properties within the PD in practice auxiliary quantities like eigenfrequencies and eigenmodes are used /14/. To reason on the acoustic behaviour of the product experience about correlations between acoustics and eigenfrequencies and eigenmodes is required and different operational states have to be considered to reason on. Another approach for quantitative evaluation of structure-borne noise is based on the structural intensity (STI) /15, 16/ or structure-borne sound intensity (SSI) /17/. Based on the analysis of the energy paths, local starting points to generate impedance jumps through design changes (e.g. removal of material, increase in stiffness or additional damping) can be derived and evaluated. Evaluation of the SSI requires models of the product defining dimensions and material characteristics. Current research of Adams et al. /18/ is focussing on scaling laws to determine the acoustic properties of new designs with high geometric similarity. Here the focus is on approximation rather than exact propagation in order to support the design of type series. Lohrengel et al. /19/ propose a combination of numerical simulation and non-contact measurement to evaluate the impact of locally modified structures on the acoustic behaviour. This work again highlights the need of detailed product modelling including exact dimensions and material definition models or even prototypes.

Property Determination in Machine-Acoustic

In the field of machine acoustics extensive research has been done to develop numerical methods for exact propagation and emulation of acoustic properties. Established methods are the raytracing method /20/, the statistical energy analysis (SEA) /21/ as well as the boundary element method /22/ and the finite element method /23/. These methods allow for frequency dependent calculation of sound transmission. The detailed modelling requires an exact determination of dimensions, material as well as contact conditions (e.g. between components) of the product under development and result in high simulation efforts. At the same time great expertise is needed to derive conclusion on the perceivable acoustic behaviour. In consequence the methods mentioned are mostly used by experts in the PD in cases when the acoustic behaviour of the product does not fulfil the given requirements.

Conclusions and Current Challenges

Existing approaches are based on a range of methods differing with regard to required design determinations and accuracy of results. From an engineering design perspective the following challenges can be derived:

- There is limited methodical assistance to support a breakdown of acoustic properties form system level to subsystem levels and thus to facilitate the evaluation of requirements and conflicts during the PD process.
- Existing methods cause (re-)modelling effort and require extensive experience to assess the acoustic behaviour based on auxiliary quantities. The methods are hard to integrate into the PD process.
- There are rarely approaches to provide (qualitative) information about acoustic behaviour of reoccurring solution elements like different types of connections or recurrent design arrangements like housings.

These challenges highlight the need for research on the integration of analysis and evaluation activities into the PDP based on shared models for acoustic behaviour and other product properties. Premises and fields of research will be presented in the following section.

Towards a DFAc Methodology

Objective of this section is to highlight existing and needed fundamentals to originate a DFAc methodology. Premises and fields of research formulated here are intended to encourage a common understanding and serve as a basis for systematic planning of research activities in collaboration of acoustic and engineering design researchers.

Premises for a DFAc Methodology

Considering the elements of DFX methodologies introduced, see Figure 2, some premises and assumptions have to be formulated for structured research. Focussing on the most relevant elements there are the following premises:

- *Theory of technical systems.* Acoustic properties are positioned as external properties like damping, echo, noise or frequency response are included in existing theories /8, 24/. Considering the classification properties proposed by Hubka, acoustic properties have to be understood as ergonomic properties since they describe an influence of the product on human beings.

- *Theory of disposition*. Acoustic properties are strongly depending on the mechanical structure of the product which influences e.g. transfer path. Effective optimization of acoustics therefore have to be taken into account structural characteristics and dependencies between different acoustic properties of different levels like assemblies, subsystems and system. A DFAc methodology has to support analysis, evaluation and adaption of acoustic properties in different design stages, see Figure 1 and take into account uncertainties of geometry and material specifications of early design stages.
- *Concept of meetings*. Acoustic properties are rational properties focussing on the use phase of the future product. On the one hand the influence of acoustics is depending on the use context of the product. On the other hand the acoustic behaviour itself is affected by the operating conditions of the product. Therefore, analysis and evaluation of acoustic properties requires the specification of the use context and (changing) operating conditions.
- *Classes of relations.* Focussing on acoustic properties classifications of relations between acoustic properties on different levels are needed. As a part of a DFAc methodology identification and evaluation of relations should support the decomposition of requirements. Moreover relations have to be evaluated with regard to the use context which should go in line with the specification of the use context and interacting systems (see concept of meetings).
- *Concept of universal virtues*. Integrated into the PD process, design activities to analyse, evaluate and optimizes acoustic properties have to be based on existing product models in order to reduce modelling efforts and thus, allow fast evaluations of design proposals and stakeholder collaboration based on shared models.

The DFX elements *symmetry* and *basic pattern* are not explicitly mentioned for the following reasons: *Symmetry* in the context of design for acoustics does not relate different life cycle systems like PD and production since the life cycle focus of acoustics is the use phase. The concept of symmetry in a DFAc methodology thus is not relevant with regard to the life cycle but other product properties to be considered in the PD phase. *Basic pattern* are the essential elements of a DFAc methodology. With regard to existing research there is already a great body of knowledge. Future works should focus on the extension and classification of this knowledge as well as the contentious integration of knowledge of design practice and new material combinations and production technologies.

Fields of Research to Originate a DFAc Methodology

Based on the analysis of existing approaches and the premises formulated initial fields of research can be outlined. The research fields described below should serve for a structured composition of a DFAc methodology focussing on needs and constraints from design practice as well as design theory and methods form acoustic research. Taking into account the steps of evolution of DFX methodology, prior fields of research should be:

- *Acoustic characterization of solution pattern.* Solution pattern are of great relevance for effective PD and reuse of knowledge. Focusing on acoustic properties, solution pattern have to include information on the mechanical structure as well as operation conditions like stimulating forces. In order to provide assistance for decision-making in early design stages a great potential is expected in investigating the informational value of geometric similarity ratios indicating for instance the effect of basic dimensions and arrangements on the sound transfer and emission. Here, an emphasis should be on mechanical structures that are relevant for the sound transmission, like mechanical joining and connection elements. As well as mechanical structures relevant for sound emission, like housings.
- *Visualization methods for acoustic properties in the PD.* Since acoustic properties result from different product characteristics and are hard to evaluate in particular for engineers with low experience, there is a need for visualization techniques of acoustic properties based on auxiliary quantities. Research therefore, should focus on techniques to visualize acoustic properties in early design stages. Here, the focus should be on the visualization of the transmission path between the excitation and emission as well as points of sound emission. A major requirement for the investigation of visualization methods is the integration of commonly used product models in conceptual and embodiment design in order to enable evaluation and identification of goal conflicts with further product properties.
- *Specification of use and operation conditions to evaluate acoustic behavior.* In order to evaluate the relevance of acoustic properties as well as boundary conditions and impacts on the acoustic behavior like operations conditions including stimulating forces a specification of use and operation condition is essential. This research field will focus on the investigation of methods form Model-based Systems Engineering (MBSE) in order to support definition of operation states and interfaces. Here, a focus will be on the allocation, refinement and decomposition of requirements form system level to the level of single elements.

The outlined fields of research towards a DFAc methodology has to be seen as a starting point and will be detailed with regard to specific research questions, objectives and applications.

Discussion and Conclusion

In this contribution fundamentals to originate a Design for Acoustics methodology were outlined. Therefore, the elements of Design for X methodologies were described and mapped to the field of acoustics. Since acoustic is a complex product property, relevant in the use phase of the product, the elements *theory of technical systems*, *theory of disposition*, concept of meetings, *classes of relations, concept of universal virtues* and *basic pattern* are defined as essential elements of a DFAc methodology. Based on the analysis of the evolution of established Design for Manufacture methodology three fields for further research were identified. This contribution presents a basic review and definition of research towards a DFAc methodology. In order to detail the fields of research outlined, further analysis of the state of the art as well as a clarification of research objectives and field for application is needed.

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