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ANALYZING TRANSDISCIPLINARY DESIGN PROCESSES IN INDUSTRY – AN OVERVIEW

Kilian Gericke
Engineering Design and Methodology Group
University of Luxembourg
Luxembourg
kilian.gericke@uni.lu

A.J. Qureshi
Lucienne Blessing
Engineering Design and Methodology Group
University of Luxembourg
Luxembourg

ABSTRACT

Integrated product design and development in today's highly competitive, demanding and economically challenging world is a complex process depending upon input of many individuals, groups, organizations and even communities, which collaborate to realize the product. Due to the multi-technology nature of modern products, the design process requires multi-disciplinary resources.

Engineering design literature provides an extensive knowledge base of product design processes, most of which are specific in an explicit or an implicit way to a specific discipline. This is because some time ago, the products were perceived to be rather mono-disciplinary.

Recently, design processes have been described for integrated products from inter-disciplinary and multi-disciplinary team perspective (e.g.[1]), however, they too take product specific and discipline specific point of view.

This paper takes a transdisciplinary perspective towards product design and presents results from an empirical study carried out to analyze the design process of different integrated products belonging to different disciplines/industrial segments; all of which involve multi-disciplinary or transdisciplinary involvement.

A framework based on key findings from the transdisciplinary consolidation of academic design process models presented by Gericke and Blessing and Eisenbart et al. is developed and used to provide answers to the following research questions:

- How well does the literature based trans-disciplinary design process apply to the trans-disciplinary industrial context?
- Are there similarities between design processes across organizations regarding presence of process stages and design states?
- Are there any elements that deviate from the literature-based framework?

1 INTRODUCTION

Contemporary product development has transformed from being mono-disciplinary to increasingly trans-disciplinary. Specific disciplines are necessary but not sufficient to tackle complex and large scale design problems [2]. Technology convergence and specialization of the knowledge are two distinctive trends that have become pronounced.

Technology convergence means that functionalities of modern products and product service systems integrate technologies from more and more distinct disciplines e.g. mechanical engineering, software development, electronics, service design, and industrial design, which all have further specializations. This integration of distinct technologies results in the necessity of intervention of specialized experts from different disciplines all along the product lifecycle [3].

A related trend is an on-going knowledge specialization. According to which, it is no longer possible to become specialized in all the domains of knowledge, required for the development of multi-technology products. As a result of this development, people with specialized skills are needed to work together to accomplish a project, necessitating expertise in trans-disciplinary knowledge.

These two trends are implicitly visible in industry. However, trans-disciplinary design has not been considered sufficiently in earlier work on design methodology [4]. While multi-, inter- and trans-disciplinarity are terms that are often interchangeably used in the literature, taking a multi- and inter-disciplinarity perspective is interpreted here as focusing on the transfer of knowledge and methods between specific disciplines. Transdisciplinarity, as opposed to multi- and inter-disciplinarity, concerns that which is simultaneously between disciplines, across different disciplines, and beyond all disciplines [5]. Ertas et al. define trans-disciplinary design as the integrated use of the tools, techniques, and methods from various disciplines [2].

The interview study presented in this paper builds on key findings from the trans-disciplinary consolidation of academic design process models presented by Gericke and Blessing [6] and Eisenbart et al. [7]. The research is based on an empirical study carried out in industries involved in trans-disciplinary design of products, i.e. requiring technologies and knowledge from different disciplines, thus requiring collaboration of experts from different engineering and design disciplines.

The research program, of which this study is part of, is guided by the following overall research questions:

- Is there a potential for coupling the discipline dependent design processes through a generic trans-disciplinary design framework?
- What are the commonalities in terms of the process characteristics (design stages, design states, etc.) across disciplines which may serve as basis for trans-disciplinary design?

2 SHARED ELEMENTS OF DESIGN PROCESSES ACROSS DISCIPLINES

> *"Engineering processes are the glue that hold the activities within product development and design together. Engineering processes structure these tasks appropriately and ensure the correct and timely use of the appropriate approaches & procedures, methods, data, and tools in order to improve the design process, improve products and services, and properly document product development processes and the products themselves."*[8]

Engineering processes are embedded in an environment i.e. their context [9,10]; which can be described on different levels of resolution considering different influencing factors or groups of influencing factors e.g. the design task, prerequisites of the design team, individual prerequisites, and external conditions [11]. An industrial design process and its context are interdependent. A multitude of attributes is required to describe the complex interactions that take place during product development. This is not sufficiently represented in process models from literature.

Most academic process models, especially those which serve as a basis of design methodologies, aim to be branch independent, i.e. they represent good practice within a particular discipline, without focusing on specific products. These process models are abstract and represent product development in a certain discipline by a common stage division, related main activities, and deliverables.

Some authors conducted comparisons of design methodologies and academic design process models (e.g. [12–16]). An overview and consolidation of existing comparisons of design methodologies and process models is provided in [4]. Based on the analysis of the existing comparisons it was concluded that design processes have similarities across disciplines: they have a core of common design stages; they propose a stepwise, iterative process.

Gericke and Blessing [6] compared 64 design process models from 9 disciplines i.e.: mechanical engineering, industrial design, systems engineering, building design, software design, service engineering, mechatronics, product service systems and transdisciplinary approaches. They identified the following set of design stages which can be found in the process models across the reviewed disciplines: *establishing a need, analysis of task, conceptual design, embodiment design, detailed design, implementation, use, and closeout*. Typical activities within these stages are identified and differences between disciplines are discussed.

The review of Gericke and Blessing [6] also shows that most of the process models build on the same concepts developed in the 1960's or 70's. The evolutionary development of the process models may have led to the similarities, which can be observed nowadays.

Eisenbart et al. [7] performed a trans-disciplinary analysis of design methodologies with a focus on design models and design states, which is complementary to the study of Gericke and Blessing. They analyzed 31 methodologies from 5 disciplines. A design state is defined as the incorporation of all the information about a design as it evolves [17]. Apart from supporting communication, design models are important means for capture and storage of information generated in the progress of product development: new information is typically stored in a new or updated design model. Eisenbart et al. [7] propose the following list of trans-disciplinary design states: *problem statement, context analysis, need, product idea, product proposal, design object specification, requirements specification, product functionality, working structure, conceptualization, preliminary layout, layout, and production documents*.

The results of the trans-disciplinary analyses of design stages and design states provide two dimensions for formulating a framework for describing transdisciplinary design processes.

However, the comparisons are based on process models and design methodologies from literature which themselves are based on concepts developed several decades ago. Design practice has developed further. New tools are available; products and design practice have become transdisciplinary. Hence, the question arises to which extent the elements of the design process framework, which were identified as common across the disciplines, do fit to current transdisciplinary design practice in industry.

In order to provide more detailed guidance for the further development of design methodology, new empirical studies are necessary, aiming at an identification of shared elements of design processes of current design practice and supporting the identification of transdisciplinary elements of product development. Such insights are expected to bring new arguments and new facts into the debate.

The study presented in this paper aims to provide answers to the following research questions:

- How well does the literature based trans-disciplinary design process framework (considering product life cycle phases, design process stages, and design states) apply to the trans-disciplinary industrial context?
- Are there similarities (commonalities) between design processes across organizations regarding presence of process stages and design states?
- Are there any elements that deviate from the literature-based framework?

3 STUDY DESIGN

The study presented in the following provides a qualitative analysis of current transdisciplinary product development and design practice with a strong focus on the product development and design process. In line with the earlier discussion of the need to have a multi-layered understanding of trans-disciplinarity at different levels of abstraction, the study has been designed to aggregate and analyze the information in a three level frame of reference. This includes aggregation of contexts across organizations, inside organizations, and within an individual project. The contexts include fundamental attributes such as type of industry, market areas, products, expertise and disciplines of the participants.

Data collection

The data was collected through semi-structured interviews with industrial professionals. 23 interviews were carried out over a period of four months. A pilot interview prior to the start of the interviews series was used to verify the understanding of the questions and to modify the questionnaire wherever necessary.

The interviews were carried out via in person interview, video conferences and telephonic interviews and whenever possible done in the native language of the interviewee. Each interview lasted between two and three hours.

The semi-structured interviews are based on a questionnaire, which was available in a web-based format as well as in paper form. The questionnaire consists of 87 questions covering the following areas: Factors describing the product development context (e.g. company, product portfolio and market), background of the interviewee, the company's design process and its documentation, and a reference product design project, which is representative for the organization.

Choice of interviewees and organizations

The choice of interviewees was a critical factor in order to achieve a balance between details on transdisciplinary design activities and the required holistic overview about the context in which these activities took place. Ideal candidates were identified to be designers or design managers who possess experience in their field of expertise and possess a management overview of the design project they referred to during the interview. This restricted the interviewees to be experienced designers and engineers with current management roles in the organizational hierarchy.

In line with the transdisciplinary focus of the study, it was decided not to restrict the sample to a certain industrial, product or discipline specific context. The sample was selected to reflect a diverse mix of different industrial segments, ranging from building and public works to chemical process industry; product variation from creation of a web-portal (and related services) site to automobile design. For each product, it was assured that the product integrates different technologies, thereby necessitating the involvement of different individuals with specific skills and expertise. This assured two layers of transdisciplinarity: a layer of transdisciplinarity on the organizational level i.e. aggregation of information across different organizations and a second layer of transdisciplinarity of professionals within these organizations involved in transdisciplinary design of products.

An industrial classification according to employment size as prescribed by the European Commission classification [18] was used to classify the organizations where participants worked. The organizations were divided into two main categories i.e., small and medium sized enterprises (SME) and large enterprises. The SME were further divided into: micro enterprises, small enterprises, and medium-sized enterprises.

4 RESULTS

4.1 Sample profile

Industrial profile of organizations

The participants belong to organizations from 10 different countries based in 14 different countries on four continents. 17 organizations were from Western Europe whereas the rest were from outside Europe. Two distinct categories can be discerned: Large multinational organizations with global technology development centers and global presence (employee size >250, n=17) and small highly focused design studios / design organizations (employee size <50, n=6). The second category is due to inclusion of industrial design discipline as well as the inclusion of SMEs.

The majority of the participants work in large design teams (250-1000 people). From a business perspective, the minimum and maximum reported revenues for the organizations were between 6 Million to 450 Billion Euros.

The organizations are classified according to the classification of European Commission [19] which classifies the industries according to the area of activity as well as the products. The organizations represented by the participants accounted for 16 areas in terms of the primary, secondary and tertiary activities in a given segment as shown in Figure 1.

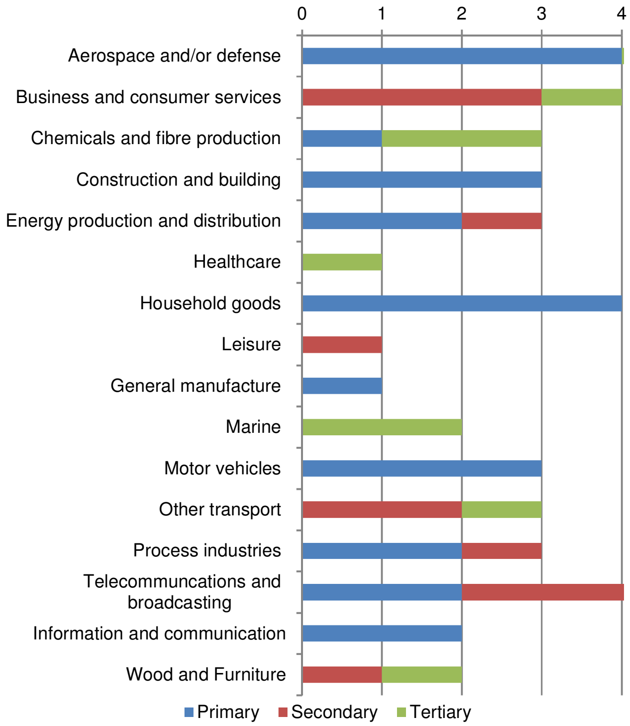

Figure 1. MARKET AREAS COVERED BY THE ANALYZED ORGANIZATIONS

All of the organizations are in the business of designing and developing products (not limited to physical products but also non-physical products such as software). The majority of the organizations are exceptional i.e. considered among the market leader in their respective market areas based on revenues and market share. The organizations operate on a broad range of markets covering consumer and industrial segment products such as aerospace and defense, household goods, motor vehicles, telecommunication systems, business and consumer services.

Customer type and production type

An analysis of the organizations' main products in order of importance of business generation was done in terms of products, customers and manufacturing model. A total of 47 products were ranked for end customer type and the manufacturing process. More than half (n=28) of the products were intended to be for the business customers (B2B) followed by products intended for consumers (B2C) and governments (B2G). The manufacturing model represented the most was mass production (n=23).

Organization's competencies

The participants were asked to rank the major strengths of their organization in terms of their capability in the sector of design, manufacturing and sales and system-based sector of activities. All the participants ranked their organization to have major competency in at least one of the sectors (Figure 2) most of them (n=19) in design and manufacturing. Four participants ranked their organization to have major competency in all the sectors. 12 participants ranked their organization as having at least two major competencies. The majority (n=20) of the participants describe their organizations as systems integrator and service provider, according to the scheme of Dalziel [20] (Figure 3).

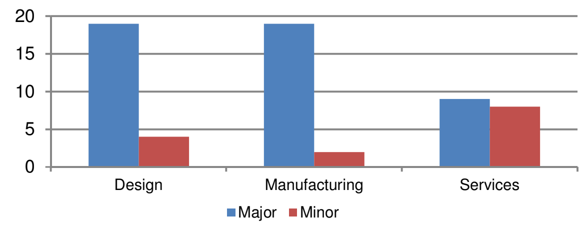

Figure 2. MAJOR COMPETENCIES

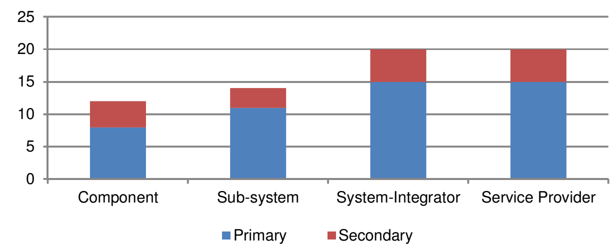

Figure 3. SYSTEM LEVEL

Organization's capabilities

The participants were asked to evaluate their organizations' capabilities on basis of the organizational strategy and design and development capabilities. More than half of the participants assessed their organizations' capabilities using the highest level (out of 5) describing the maturity in the particular areas. They reported that:

- Their organizations have integrated procedures for design and development supplemented by market analysis and business planning to support these procedures. (level 4 and 5: n=14)
- They employ graduate engineers and industrial designers; they use the latest tools such as CAD and CAE. (level 5: n=13)
- They pre-plan the development tasks and resources needed in detail, fix targets for project cost and timing for each project phase, continuously monitor time and cost and take corrective action to ensure that both are met, and hold review meetings at milestone dates to approve continuation to the next phase. (level 5: n=13)

Interviewee Details

The participants had a mean experience of 12.3 years in their respective fields and had worked on average in two organizations before working for the current organization. More than half (n=15) of the participants interviewed held hierarchical roles related to middle or upper management (project lead, corporate manager, executive manager) as opposed to technical specialists.

The participants interviewed represent a sample from 12 different disciplines i.e.: mechanical engineering, chemical engineering, industrial design, product development, aerospace engineering, mechatronics engineering, industrial engineering, computer science, electronics engineering, management, telecommunications engineering, and architecture.

4.2 Design task, product and team characteristics

In order to get consistent answers to project and product specific questions, the participants were asked to select one reference project in which they had been involved. The project included the development of a product, system, artifact or a service that was representative of the organization's most general design activities. The project had to be ideally completed or in a mature stage.

The participants were asked to characterize the reference product development project as original design or evolutionary design. 13 participants (61.9%) described it as evolutionary design as compared to 8 participants (38.1%) with original design.

The products developed in the selected reference projects contain technologies from multiple disciplines, thus represent what can be called a transdisciplinary product, such as jet engines, cell phones, process plants, satellites, motor vehicles, consumer electronics.

Referring to the particular project the participants were asked to identify distinctly different roles and disciplines, which were involved. Each participant described a minimum of four distinctly different roles in the project (up to ten roles for five participants). People belonging to 28 different disciplines held these roles. The most frequently occurring disciplines were mechanical engineering, management, chemical engineering, architecture, civil engineering, industrial engineering, industrial design, systems engineering, electrical and electronics engineering, software and computer science, sales, logistics & supply chain management, and finance.

4.3 Design process – organization level

Through a set of specific questions, the participants were asked to define and describe the design process utilized, promoted and supported by the management of their organization. Results presented in this section refer to the design process on organization level.

Process documentation

The participants were asked if their organization has a documented process to support product development and related activities. 20 participants responded that a documented process is present whereas three participants responded that no documented process is present. These three participants shared common characteristics including: a micro-sized design and development team (1-10 people), two of them belonged to micro industry (¯ 10 employees). Both participants are industrial designers.

Process morphology

One of the aims of the interview study was to verify the stage based nature of the design process in a transdisciplinary design context, which was observed as a characteristic of academic process models [6]. Here a stage is defined as "a subdivision of the design process based on the state of the product under development" as proposed in [14].

The participants were asked if their organization's product development and design process is divided into stages. 22 out of 23 participants responded that the process is divided into stages, with the majority (n=14) subdividing their organization's process into 4 to 6 stages.

Life cycle coverage

Due to diversity of the market areas of organizations, disciplines and products, the organizations' product development and design related activities were mapped to 5 generic transdisciplinary phases of product life adapted from recent research in design processes [6] and augmented by work on the product life cycle [21]. These phases are: *Imagine & establish a need, Define, Realize & implement, Use & support, End of life*.

The mapping of the organization's design process stages to these phases was done by the participants themselves supported by the interviewer and detailed descriptions of the particular phases. All the participants reported that the 'imagine' and 'define' phases are covered. Most organizations (n=21) cover the 'implementation' phase. 17 cover the 'use' phase and 12 the 'end of life services'.

In order to gain more insight and details into the organizations' life cycle coverage and to develop a transdisciplinary basis for the comparison of major stages and activities, each of the product lifecycle phases (with exception of the last phase) described above was subdivided into four main subdivisions. These were selected from the models analyzed in [6] representing major activities/stages in each particular phase (see Figure 4).

The participants could choose if an activity or stage was carried out by their organization with full internal responsibility of task completion (fully internal), or was done partially with involvement of other collaborators such as sub-contracting partners, consultants etc. (partially internal) or was completely given for completion/execution to an external partner (fully external).

Certain interesting observations were made. The frequency of the responses that a subdivision is carried out partially with help of a partner or is completely outsourced is highest for the sub division of detailed design, production systems development, manufacturing and assembly. This indicates the trend of the design driven characteristics of these organizations and their preference to delegate the tasks related to detail design and manufacturing to external partners. It points to the fact that the companies tend to have a greater control on the decision-making and development work in the earlier stages until a point where the fundamental decisions about the product have been firmed up. This means that the organizations intend to have a greater internal autonomy and control on functional design, system level design and architecture of the product. After the embodiment, the organizations tended to sub contract the succeeding stages.

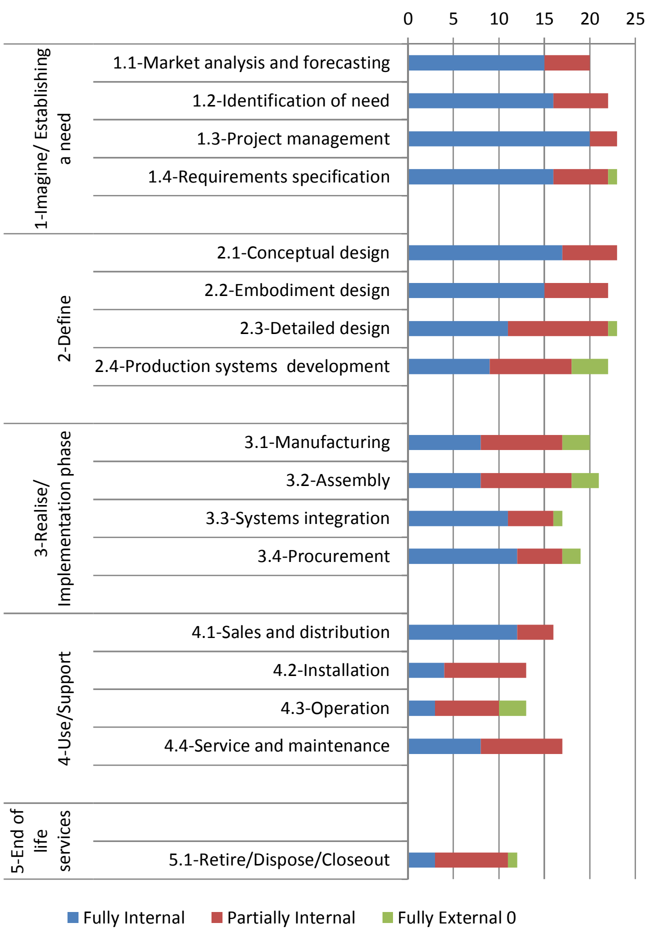

Figure 4. PHASE DETAILS

Most of the people interviewed depended upon partner organizations having expertise in specific subsystems for detailing of the sub-systems/components. This was especially true in aeronautics, defense and automobile, where a very tight integration with the partners was observed. The partners did most of the detail design, which was in turn integrated by the main company. The partner eventually provided the finished sub-systems to be directly integrated in the main system. Subsequently, it can be observed that the subcontracting decreases in the 'systems integrations' part possibly due to the fact that procured or manufactured sub-systems are then integrated by the main organization itself.

The ratio of outsourcing to inside work may be an indicator of an organization's model of value creation in its process. A possible application of this consideration is the shift towards PSS as a source to create value from the services rendered to or through the product designed in house.

The least number of responses for inclusion of a phase were received for phase 5 'End of life services' (n=12). This phase also received the least amount of responses full internal involvement of an organization. Most of the participants indicated that this phase is not considered well enough in their design process model. This reflects the current product life cycle considerations, as most of the organizations do not employ end of the life considerations in design as well as a final step in the product life. The effect of this is fuzziness for different stakeholders for the end of life of the product.

4.4 Design process – project level

The results presented in this section refer to the design process on project level i.e. the interviewees were asked to refer to a reference project, which represents the organization's design activities. Therefor the project specific results may differ for some cases from the results on organization level.

Life cycle coverage

Being asked for the life cycle phases and design activities that were considered in the project, 20 out of 22 interviewees reported that the imagine phase was covered. The define phase was covered in all the projects, whereas only 15 projects covered the realize phase. Nine projects covered the use phase and only three interviewees stated that the end of life was covered by the projects. Design stages and activities that were mentioned most often are: conceptual design (n=21), detailed design (n=20), requirements specification (n=19), embodiment design (n=18), and project management (n=16). A detailed overview of the responses is provided in Figure 5.

During the interviews, it was corroborated that project management is not performed only at the beginning of the project, but is a continuous activity.

Being asked for the key activities in the design stages the interviewees reported mainly design related activities as expected and already covered by the framework. Some interviewees, who were involved in the development of complex systems and new product platforms, added activities such as demand management (i.e. estimation of take rates), target pricing, and creation of prototypes.

An analysis of dependencies between individual context factors such as *novelty* of the design (evolutionary vs. original design), *lifetime of the product* (years the product will be used), *project duration*, *type of production* (one off, batch, mass production, continuous process, virtual product), *market area*, and the life cycle coverage was done. Factors related to the product like *market area* and *type of production* seem to have a dependency with the life cycle coverage. Interestingly novelty and product lifetime seem to have no relation. Because of the small sample size and the large number of factors having an influence on the design process no analysis using inferential statistics was performed.

Even though market area and production type seem to have a dependency with the life cycle coverage no entirely clear pattern can be observed.

In order to identify patterns of factors (combinations of factors) having an influence on the life cycle coverage the projects were clustered according to their life cycle coverage into four groups (see Figure 5):

- Projects belonging to group 1 cover only the 'Imagine/Establishing a need' phase and the 'Define' phase.
- Projects of group 2 cover the 'Imagine/Establishing a need' phase, the 'Define' phase, and the 'Realize/Implementation' phase.
- Projects of group 3 cover additionally the 'Use/support' phase.
- Projects belonging to group 4 cover all five phases of the generic product life cycle.

The four groups show some similarities. In the following, some of the features, which distinguish the group from other groups, are reported.

Group 1: Projects belonging to group 1 are mainly consumer products and household goods, such as washing machines, furniture, television, and camera. Exceptions to this are projects developing a power transformer and a pressure vessel.

Group 2: Projects of group 2 were characterized as being technology push as well as market pull development projects. Some of them are customized products and complex systems. The products belong to the market areas: telecommunication and broadcasting, aerospace and defense, motor vehicle, and process industries. Examples are parts of car interior, communication network hardware, smartphone, subsystem of oil production facility, supply chain management software, and a sub system of a rocket.

Group 3: Products developed in the projects of group 3 show a rising complexity and are described as high-risk products, and platform products. They are intended for market areas such as aerospace and defense, motor vehicle and software. Examples are a chemical production facility, a complete satellite, a billing system (software), and an electronic assistant for car driver.

Group 4: Products of group 4 belong to market areas aerospace and defense, motor vehicle and software. Examples are a city bus platform, a satellite platform, and web-portal for a public institution (including web-design, software development and the design of related services). These products were described as customized products, technology push, complex system, and platform products.

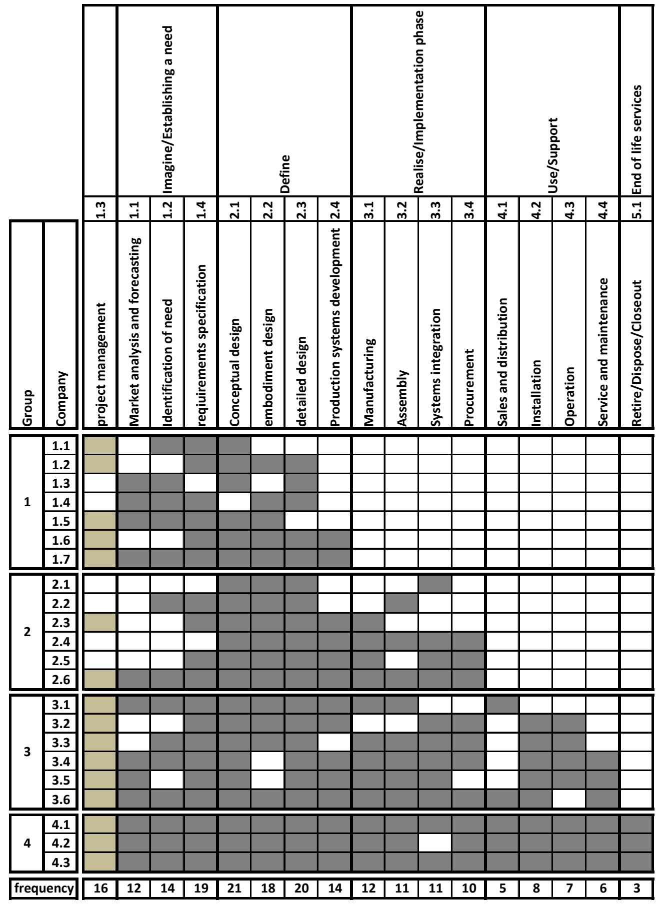

Figure 5. MAPPING OF REFERENCE DESIGN PROJECTS

During the interviews the participants were asked to select from a list of ten schematic representations of design processes (like waterfall, spiral, stage-gate, V-model), the form that best represent the shape of the organization's design process. Interestingly no interviewee from group 1 used the V-shape as described for example in the VDI guideline 2206 [1] to describe the visual representation. In all other groups, this shape was selected several times.

A pattern that can be observed is that the life cycle coverage is bigger for projects showing a rising complexity of the products under development and high risks related to their operation as well as increasing financial risks for the company (in case of platform development projects).

Importance of process stages

Being asked for the design stage in the reference project that is perceived as being the most influential, the majority of the interviewees (n=15) stated that the conceptual design stage, followed by embodiment design (n=8) are the most influential design stages (see Figure 6, n=22, multiple answers were possible). Interestingly no interviewee mentioned an activity from the implementation phase.

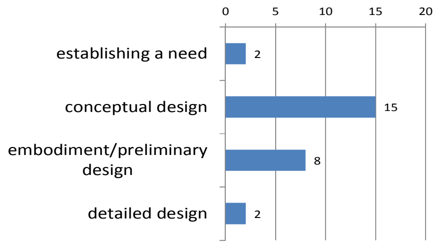

Figure 6. PERCEIVED IMPORTANCE OF DESIGN PROCESS STAGES

Iteration

All interviewees reported, that in the reference design project iterations occurred. 19 interviewees said these iterations were expected, thus de facto planned. 18 interviewees said some of the iterations were unexpected. 14 of the interviewees reported that major iteration occurred. Examples of reasons that resulted in major iterations are for example: changes of requirements or design concepts, problems with sub-contractors, identification of design flaws during design reviews, and problems at interfaces of the product.

4.4 Design states and deliverables in the design processes

The selection of the design states was done by the participants themselves supported by the interviewer and detailed descriptions of the particular design state. It was noted that although the participants used industry and discipline specific terminology for describing the design states used in their product life, they identified their design state with the generalized design state with ease. Each of the design states proposed was selected at least 13 times.

The detailed frequencies are as follows: requirements specifications (n=20), preliminary layout (n=19), needs to fulfill (n=18), conceptualization (n=18), product functionality (n=18), production document (n=17), product idea/proposal (n=16), design objective (n=16), market research (n=14), problem statement (n=13).

Even in companies describing their own process as stage gated, design states were mentioned to be relevant across different process stages, indicating continuous work using the same way of representing information but on different levels of maturity (see Figure 7). Figure 7 represents our qualitative interpretation of what the interviewees reported. Based on the interviews we subdivided the presence of the design states into three phases: pre-delivery, delivery and post-delivery. Pre-delivery means that information represented by a design state is not yet complete or in an immature stage. Delivery means that a first release of the design state can be communicated, even though this might be refined or modified in the post-delivery phase. Especially documents representing the design states 'requirements specification' and 'system functionality' were reported by several interviewees to be relevant across multiple stages within a single project, thus being maintained and actualized during the project.

Some of the interviewees reported, that they use an additional design state, which they call systems architecture. Interviewees involved in complex platform development projects reported this.

		Imagine/Establishing a need			Define				Realise/Implementation				Use/Support				End of life services
	1.3	1.1	1.2	1.4	2.1	2.2	2.3	2.4	3.1	3.2	3.3	3.4	4.1	4.2	4.3	4.4	5.1
design states	project management	Market analysis and forecasting	Identification of need	reqiuirements specification	Conceptual design	embodiment design	detailed design	Production systems development	Manufacturing	Assembly	Systems integration	Procurement	Sales and distribution	Installation	Operation	Service and maintenance	Retire/Dispose/Closeout
market research	post	d	post	post	post	post											
needs to fulfil	post	pre	d	post	post	post											
problem statement	post	pre	d	post	post												
product idea/proposal	post	d	d	post	post												
design objective	d	pre	pre	post	post	post											
requirements specification	post	pre	pre	d	post	post											
product functionality	post	pre	pre	pre	d	post							post				
conceptualisation	post		pre	pre	d	post						post	post				
preliminary layout	post			pre	pre	d	post	post				post	post				
production document	post				pre	pre	d	post	post	post	post	post	post	post	post	post	post

pre: pre-delivery; d: delivery; post: post-delivery

Figure 7. PRESENCE OF DESIGN STATES IN PRODUCT LIFE CYCLE

5 DISCUSSION

One of the main aims of the empirical study was to evaluate the applicability of the literature based transdisciplinary framework (product life cycle phases, design process stages and design states) to the trans-disciplinary industrial context. Through the empirical study, this applicability was tested on three layers (trans-organizational, organizational and project).

5.1 Applicability of literature based trans-disciplinary design process framework to the industrial context

The framework adapted in this study is based on research work [6,7] that brings together one of the most comprehensive efforts in terms of diversity of disciplines in a comparison. Basing the study on the framework allowed us to assure that a reasonable number of disciplines were already considered for the empirical study.

All the participants were able to relate to the product life cycle phases on the level as proposed in the literature. It was observed that the proposed phases not only covered the entirety of the organizations product life cycle but also provided supplementary coverage, which was not currently considered by some companies. At the trans-organizational and organizational level the phases are therefore a suitable representation of the trans-disciplinary industrial design practice. At a lower level of abstraction, the participants identified the activities and stages to be the part of their organizational processes. The activities/stages of the first phase 'Imagine' were identified with the least changes. Same was the case with the 'Realise' phase, where most of the participants were able to directly map the stages to their process. The participants deliberated the most for performing the mapping of the proposed stages with their stages in the 'Define' phase. The diversity of the terminology across the disciplines and the organizations was observed the most in this phase. However, all of the participants were able to identify the entirety of their corresponding stages to the 'Define' phase.

Similar observations can be made for the design states. The participants identified all of the design states with the ones requiring the least discussion in the start and in the end. It is clear from the participants' responses that the general design process in the industry is a stage-based process. The number of the stages varies from one organization to another but they can be related to the common framework proposed.

It can be summarized from the participants' responses that at the given level of abstraction the proposed framework (product life-cycle, stages and design states) is a support that can be further developed as a framework for describing and coupling the discipline-specific processes in specific industries.

5.2 Commonalities between design processes across organizations

The study of the trans-organizational sample here has resulted into a couple of important observations.

Although, the analyzed organizations have different contexts, (e.g. market areas, size, product, manufacturing model) yet there are similarities between design processes across organizations regarding presence of process stages, design states, the form of the process model as has been shown by the empirical study.

The early phases were covered by all projects. The 'imagine' and 'define' phases are central for all organizations, which is supported by the fact that these were reported to be covered by all selected reference projects and are usually performed in-house and seldom with support of external partners. Design stages and activities out of these phases were also reported to be perceived as having the biggest influence on the projects outcome. At the same time the majority of the major iterations occurred during the define phase. Iterations are a further commonality across the projects. Almost all participants reported expected and unexpected iterations occurred during the design projects.

Other similarities seem to be dependent on product characteristics such as complexity, risks related to the project and financial risks for the company, and market area. The more complex the products and systems under development become and the higher the risks related to the operation of the product and the higher risks for the companies from an economical point of view are, the larger the life cycle coverage is. Complex systems and development projects with high risks require a more intensive consideration of later life cycle phases like 'Realize' and 'Use/Support'. Interestingly the novelty of the task (original vs. evolutionary design) and the type of production show no dependency with the life cycle coverage of the projects.

Furthermore, some interesting exceptions were found. An exception was three participants who responded that they did not have a documented design process. They however agreed that although they did not have a documented process, they still practiced a design process that they learnt from their academic training. Furthermore, they agreed that the activities/stages proposed in the framework could be related to the activities and discernible stages in the de-facto process that they practiced.

5.3 Elements that deviate from the literature based framework

The literature based design process framework provides a good basis to represent the analyzed industrial trans-disciplinary design projects. In most cases the framework covered more phases of the product life cycle and describes more design states than what is considered in the industrial design projects. Even though, in some cases additional design activities and design states, which fit to the level of abstraction of the design process framework, could be identified. A design state mentioned by some interviewees, concerned with complex platform development projects is the systems architecture, which is so far not considered in the framework. The interviewees reported that they design the systems architecture during the conceptual design stage. The systems architecture is strongly interlinked with representations of the product functionality and the conceptualization.

Activities not considered in the design process framework but reported a couple of times were allocated to the 'Imagine' phase. The participants mentioned that demand management, target pricing are important activities during that phase. They did not assign it as part of market research as many design related decisions (e.g. definition of variants, and specific requirements) were done as part of these activities.

6 CONCLUSION

The paper presents some specific results related to the complex and multi-dimensional issue of trans-disciplinary design. It can be inferred that despite a strong diversity in the market areas, types of products, and academic and professional qualifications of the sample, there are visible commonalities. These commonalities extend through the process and the design states showing that at least a sub-set of the process is based on a common creative, iterative, evaluative process. This process can be developed to be more comprehensible across the natural diversity that arises due to knowledge specialization and technology convergence. Using these commonalities a cross-fertilization or a linkage can be developed to allow better collaboration.

This is imperative because, with technology convergence and knowledge specialization, the design process has moved beyond the boundaries of one discipline, one market or an organization; rather it has become a product focused process that transcends disciplines, markets and organizations. A large number of organizations and disciplines are involved in the conception and development of a product that can be simultaneously intended for multiple markets. The authors aspire for a transdisciplinary design framework that allows such a point of view at a high level of abstraction. This level requires a coherent and uniform view on information and collaboration. Informed collaboration between disciplines promotes a crucial sensitivity in the translation between contexts and domains [22]. A trans-disciplinary approach will allow the practitioners from different disciplines to collaborate and cooperate at a level of understanding that retains their context specific information and allow its transfer and comprehension by the participating professionals from other disciplines.

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