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DESIGN PROCESS COMMONALITIES IN TRANS-DISCIPLINARY DESIGN

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ABSTRACT

Contemporary product development has transformed from being mono-disciplinary to increasingly trans-disciplinary. Technology convergence and specialization of the knowledge are two distinctive trends that have become pronounced. These two trends are implicitly visible on a cross-disciplinary interaction level in industry. However, trans-disciplinary design has not been considered sufficiently in earlier work on design methodology.

This paper presents results from an empirical study to identify shared elements of current design practice in industry and identification of transdisciplinary elements of product development. A framework based on key findings from the transdisciplinary consolidation of academic design process models presented by Gericke and Blessing (2012) and Eisenbart et al. (2011) 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 commonalities between design processes across organisations regarding presence of process stages, design states, and the form of the process model?

Keywords: collaborative design, design methodology, design practice, design process, product lifecycle management

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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 (Ertas et al. 2003). 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 specialisations. This integration of distinct technologies results in the necessity of intervention of specialized experts from different disciplines all along the product lifecycle (Ensici & P Badke-Schaub 2011).

A related trend is an on-going knowledge specialization, a^{2}ccording 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 on a cross-disciplinary interaction level in industry. However, trans-disciplinary design has not been considered sufficiently in earlier work on design methodology (Kilian Gericke & L. T. M. Blessing 2011). Transdisciplinarity, as opposed to multi-disciplinarity and inter-disciplinarity, concerns that which is simultaneously between disciplines, across different disciplines, and beyond all disciplines. Its goal is to understand the present world, of which one imperative is the unity of knowledge (Nicolescu 2005). Ertas et al. define trans-disciplinary design as the integrated use of the tools, techniques, and methods from various disciplines (Ertas et al. 2003).

The complexity of trans-disciplinary design processes foster the need for more descriptive studies of these design activities (Ensici & P Badke-Schaub 2011).

The interview study presented in this paper builds on key findings from the transdisciplinary consolidation of academic design process models presented by Gericke and Blessing (2012) and Eisenbart et al. (2011). The research is based on an empirical study carried out in industries involved in transdisciplinary 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." (MMEP SIG 2012)

Engineering processes are embedded in an environment i.e. their context, which can be described by the design task, prerequisites of the design team, individual prerequisites, external conditions, and by the result of the design process (Frankenberger et al. 1998). 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 focussing 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. An overview and consolidation of existing comparisons of design methodologies and process models is provided in (Kilian Gericke & L. T. M. Blessing 2011). 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.

In another literature study, Gericke and Blessing (2012) 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 (2012) 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. (2011) 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 analysed 31 methodologies from 5 disciplines. A design state is defined as the incorporation of all the information about a design as it evolves. Apart from supporting communication, design models are important means for capturing and storing information generated in the progress of product development: new information is typically stored in a new or updated design model (Dym 1994). Eisenbart et al. 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, conceptualisation, 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 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 process which were identified as common across the disciplines do fit to current trans-disciplinary design practice.

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 organisations regarding presence of process stages, design states, and the form of the process model?
- Are there any elements which 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 order to describe the design and development practice in a transdisciplinary context, it is not possible to fix certain context factors such as type of industry, market areas, products, expertise and disciplines of the participants. A multi-part study is needed to aggregate and analyse the complexity of contexts and the resulting commonalities and differences. The study is therefore divided into two major parts. The first part deals with the collection of a three layer frame of reference of contexts (across organisations, inside organisation, project). The second part consists of a study of the design processes of the organisations involved in design of transdisciplinary products.

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 were 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 (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 organisation.

Choice of interviewees and organisations
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 who possess experience in their field of expertise as well as a management overview of the design project they referred to during the interview. This restricted the interviewees to be experienced designers with current management roles in the organisational hierarchy.
Due to the transdisciplinary nature of the study, it was necessary to include organisations, which are involved in the design of transdisciplinary products necessitating involvement of more than one technological discipline. The professionals selected from these organisations were also involved into transdisciplinary teams designing integrated products. This assured two layers of trans-disciplinarity: a layer of trans-disciplinarity on the organisational level i.e. aggregation of information across different organisations and a second layer of trans-disciplinarity of professionals within these organisations involved in transdisciplinary design of products.
An industrial classification according to employment size as prescribed by the European Commission classification (Schmiemann 2008) was used to classify the organisations where participants worked. The organisations 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 organisations
The participants belong to organisations from 10 different countries and based in 14 different countries on four continents. Out of 23 organisations, 17 were from Western Europe whereas the rest were from outside Europe. Two distinct categories can be discerned: Large multinational organisations with global technology development centres and global presence (employee size >250, n=17); with exception of small highly focused design studios /design organisations (employee size <50, n=6). This exception is due to inclusion of industrial design discipline as well as the inclusion of SMEs.
Majority of participants work in large design teams (250-1000 people). From a business perspective, the minimum and maximum reported revenues for the organisations were between 6 Million to 450 Billion Euros.
The organisations are classified according to the classification of European Commission (Eurostat 2008) which classifies the industries according to the area of activity as well as the products. The organisations 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.
All of the organisations 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 organisations are exceptional i.e. considered among the market leaders in their respective market areas based on revenues and market share. The organisations operate on a broad range of markets, from consumer and industrial segment products such as aerospace and defence, household goods, motor vehicles, telecommunication systems, to business and consumer services.

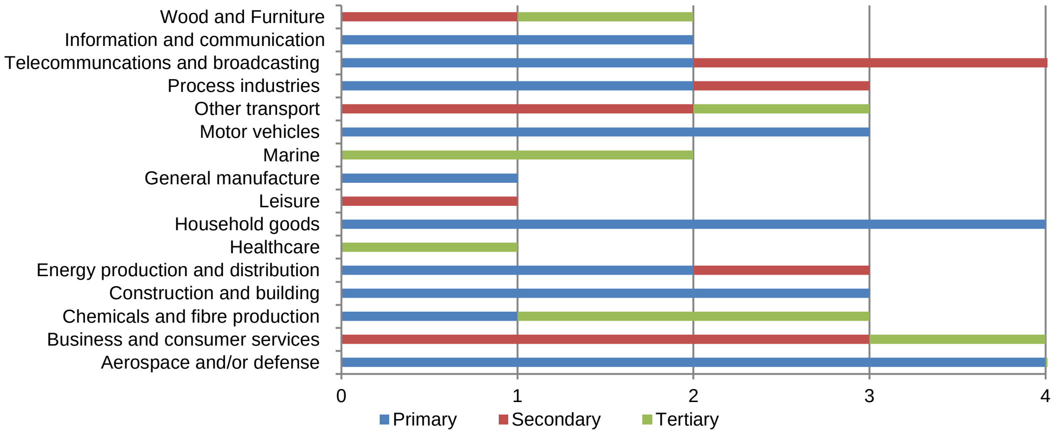


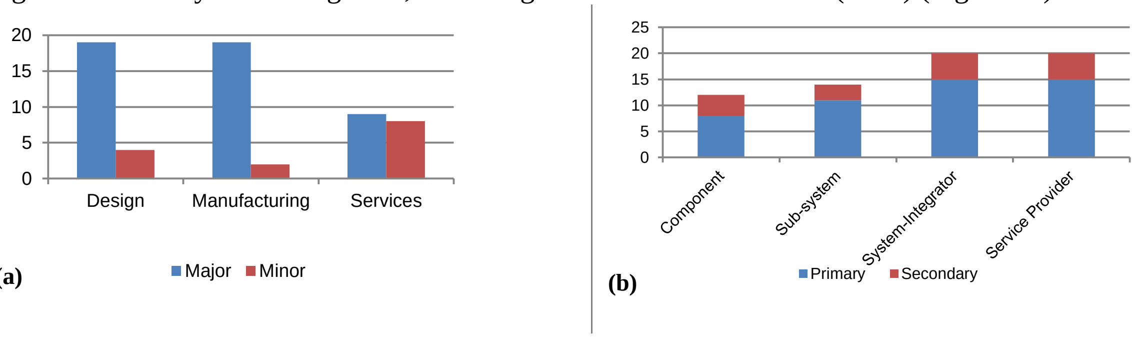
Figure 1. Frequency of organisation market areas

Customer type and production type

An analysis of the organisations' 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 along with end customer type and 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).

Companies' competencies

The participants were asked to rank the major strengths of their organisation in terms of their capability in the sector of design, manufacturing, and sales, as well as systems-based sector of activities. All the participants ranked their organisation to have major competency in at least one of the sectors (Figure 2a), most of them (n=19) in design and manufacturing. Four participants ranked their organisation to have major competency in all the sectors. 12 participants ranked their organisation as having at least two major competencies. Majority (n=20) of the participants describe their organisations as systems integrator , according to the scheme of Dalziel (2007) (Figure 2b).



(a) **(b)**

Figure 2. Enterprise competencies

Participants' evaluation of their organisation's capabilities

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

– Their organisations 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 (experience, hierarchy, discipline)

The participants had a mean experience of 12.3 years in their respective fields and had worked on average in two organisations before working for the current organisation. 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 represented 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, artefact or a service that was representative of the organisation's most general design activities. The project had to be ideally completed or in a mature stage.

The participants were asked to characterise 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 the 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

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 organisation.

Process documentation

The participants were asked if their organisation has a documented process to support the product development and related activities. 18 participants responded that a documented process is present whereas 3 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 (K Gericke & L Blessing 2012). Here a stage is defined as *"a subdivision of the design process based on the state of the product under development"* as proposed in (LTM Blessing 1996).

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

<u>Life cycle coverage</u>

Due to diversity of the market areas of organisations, disciplines and products, the organisations' product development and design related activities were mapped to 5 generic transdisciplinary phases of product life adapted from recent research in design processes (K Gericke & L Blessing 2012) and augmented by work on the product life cycle (Stark 2011). These phases are: *Imagine & establish a need*, *Define*, *Realize & implement*, *Use & support*, *End of life*.

The mapping of the companies' activities 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 companies (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 organisations’ 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 analysed in (K Gericke, & L Blessing 2012) representing major activities/stages in each particular phase (see Figure 3).
The participants could choose if an activity or stage was carried out by their organisation 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).

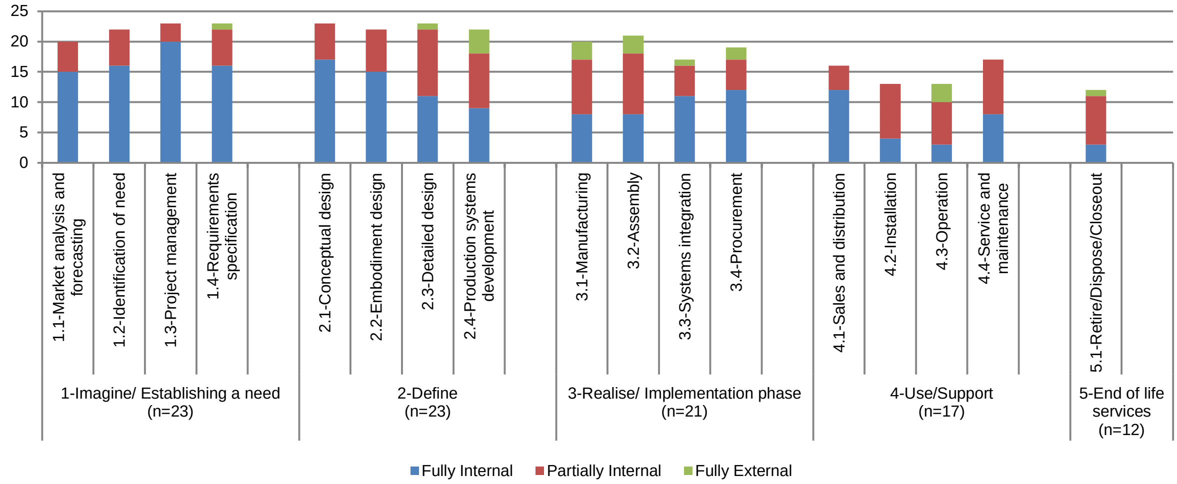


Figure 3.Phase Details

Certain interesting observations were made. The frequency of the responses that a subdivision is carried out partially with help of a partner or is totally outsourced is highest for the sub division of detailed design, production systems development, manufacturing and assembly, indicating the trend of the design driven characteristics of these organisations and their preference to delegate the tasks related to manufacturing to external partners. This trend is less evident in the ‘systems integration’ possibly due to the fact that some participants interviewed were from organisations which procured manufactured sub-systems to produce a fully integrated product. It is also observable from Figure 2b that the majority of organisations are systems-integrators.
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 organisation. Most of the participants indicated that this phase was not considered well enough in their product life.
<u>Design states and deliverables in the design processes</u>
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 fulfil (n=18), conceptualisation (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)
<u>Perceived visual image of the companies’ product development and design process</u>
After describing their companies’ product development and design process, a list of ten visual schematic representations of processes was shown to them (see Figure 4). The visual representations were derived from design process models found in literature.
The participants were asked to choose the figures that best describe their organisation’s product development and design process. They were allowed to choose more than one figure to describe the process.

During the selection process, the participants were not provided any input, help or description about the figures from the interviewers. After selecting the figures, the participants were invited to explain their selection of the figures.

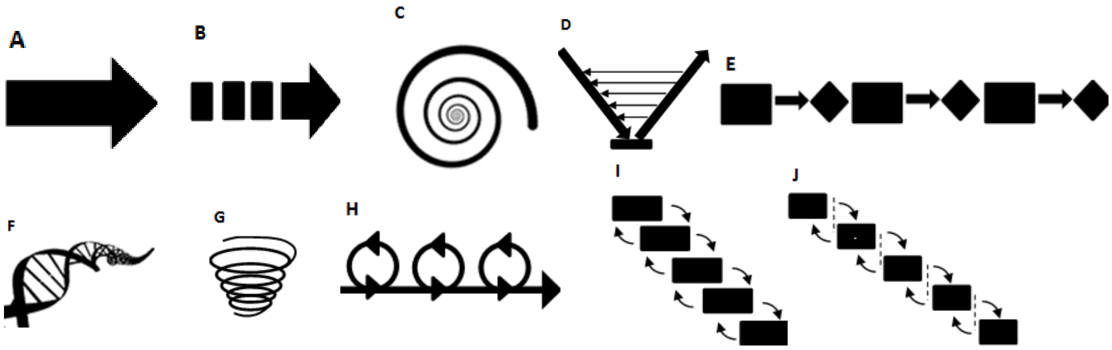


Figure 4. Image prompts for visual image of design process

Participants selected figure E the most (n=13). The second most selected figure was H (n=7) followed closely by D (n=6), B (n=5) and I (n=4).

The most common explanation for selection of E by the participants was representation of the stage based nature of the design process with presence of major decision points (reviews) at the end of each stage. They also described E as the stages and gates passed in the project for purposes of forming consensus on achieved results and planning on following activities. All of the participants used the term stage to describe the square boxes in the figure whereas they used different terms such as “gates”, “milestones”, “decisions”, “reviews”, and “consensus” to describe the diamond in the figure. Most of the participants identified the arrow as a transition from one stage to another.

The participants also highlighted the dependency of several downstream processes on the achievement of earlier milestones. The participants selected additional figures with E to describe the nature of the process within the stage. This was obvious by the second most selected figure H. This figure was selected in conjunction with E to show the iterative nature of the activities within a stage as well as the application of the inducted lessons learnt. The participants used the words such as “iteration”, “recycling”, “recursive, iterative process”, “recursive task iteration” to describe the lower level of abstraction in the design process described by the figure H.

The combination E-H, wherein E represents the higher level abstraction of the design process with H representing the process at the next level of abstraction in each stage was the most commonly described participants’ visual perception of the design process. The participants selecting the combination E-H also had the largest diversity in terms of participants’ disciplines and industry type.

D was selected only by the participants who had their academic education from Europe, in disciplines of mechatronics, mechanical or electronics engineering, and were employed in European organisations. All of the participants from telecommunication industry, aeronautical and defence industry, and motor vehicle industry choose D. These participants worked in organisations possessing competencies at different level of systems based structure classification (Figure 2b). The most common explanation for choosing the D shape was the layered and phase based design and integration process. The shape was selected commonly with the shape E resulting in a combined process E-D where participants described the design process from a management perspective by figure E in conjunction with the system based design and integration nature of the design process through figure D.

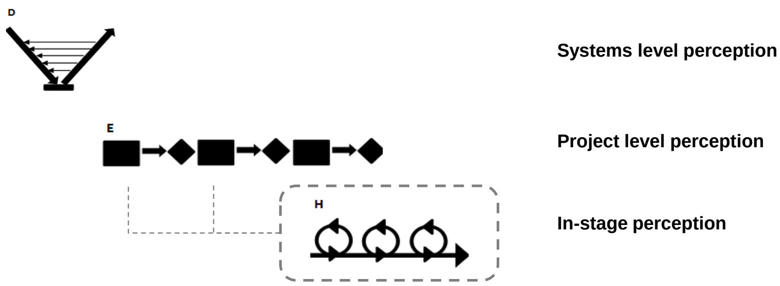


Figure 5. Perceived visual image of design process

It can be concluded that most of the participants coherently described the design process from a management perspective as an iterative stage-gated process with a further iterative process consisting of several activities in each stage (E-H). Furthermore, a group of the participants belonging to specific disciplines provides a further dimension by adding the system based description (Figure D) to the description by figures E and H (see Figure 5).

5 DISCUSSION AND CONCLUSIONS

One of the main aim 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-organisational, organisational and project). All participants were able to relate to the product life cycle phases on levels proposed in the literature. It was observed that the proposed phases not only covered the entirety of the organisations product life cycle but also provided supplementary coverage which was not currently considered by some companies. An example in this regard is the 'end of life' phase. At the trans-organizational and organizational level the phases are therefore a suitable representation of the trans-disciplinary industrial design practice.

It is however at the lower level of abstraction of activity/stages, that more interesting observations emerge. Consistent with the phase based product life-cycle, the participants identified the activities and stages to be the part of their organisational processes. The activities/stages of the first phase 'Imagine' were identified with the least changes and participants spent minimum time and effort to co-relate these stages/activities to their stages and activities. Same was the case with the 'Realise' phase, where most of the participants were able to directly map the stages to their process.

It was in the 'Define' phase that the participants deliberated the most for performing the mapping of the proposed stages with their stages. The diversity of the terminology across the disciplines and the organisations was observed the most in this phase. However, all of the participants were able to identify and map the entirety of their corresponding stages to the 'Define' phase.

Similar observations can be made for the design states. All of the design states were identified by the participants with the ones requiring the least discussion in the start and in the end. The design states with the most diversity in terminology were the ones related to the 'Define' phase. Some participants used a subs-set of the design states whereas others used more as is visible from results.

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 organisation to another but they can be related to the common framework proposed.

It can be summarised 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 for describing and coupling the discipline-specific processes in specific industries.

Inclusion of a trans-organisational sample here has resulted into two observations. Firstly, it allowed observing that although, these organisations have different contexts, (market areas, size, product, manufacturing model), there are similarities between design processes across organisations regarding presence of process stages, design states, and the form of process models as has been shown by the empirical study. Secondly, it highlights some aspects of the context and the level of abstraction necessary to truly consider the framework for trans-disciplinary design. A level of abstraction that starts from trans-organisational level to a personal level is required to truly embody trans-disciplinary design.

There were some interesting exceptions. Three participants 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 practised. It is also interesting to note here that a majority of the participants responded that the majority of the design at their industries involved evolutionary design instead of original design. This highlights the needs for a greater focus on evolutionary design instead of original design.

The presented study provides a snapshot of elements from the complex and multi-dimensional issue of trans-disciplinary design. The authors believe that transdisciplinary design should encompass the definitions of "transdisciplinarity" as defined by (Nicolescu 2005) and the more specific definition of transdisciplinary design (Ertas et al. 2003). Considering these definitions means that the focus of transdisciplinarity should not be restricted solely to design activities related to a specific product, market, hierarchical management segment, or an organisation. Rather, transdisciplinary design should encompass a holistic view in the true spirit of transdisciplinarity, i.e. a view that characterises on an abstract level, what is common and shared within and across not only disciplines, but also products, markets and organisations.

This view is imperative because, with technology convergence and knowledge specialisation, the design process has moved beyond the boundaries of one discipline, one market or an organisation; rather, it has become a product focussed process that transcends disciplines, markets and organisations. A large number of organisations and disciplines are involved in design 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 (Petre 2004). 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.

An important finding of the study is the higher level commonalities of the design process in terms of the product life phases and its subdivisions, the form of the design process, and the verification of the common design states. Using these commonalities, the authors consider it to be of significant importance to develop further, these elements in a transdisciplinary context so that a coupling of discipline specific processes may be achieved with a minimum loss of context and information.

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