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Stages in product lifecycle: Trans-disciplinary design context

A.J. Qureshi[a]*, Kilian Gericke[b], Lucienne Blessing[b]

[a]Newcastle University, School of Mechanical and Systems Engineering, Newcastle Upon Tyne, NE1 7RU, UK
b University of Luxembourg, RUES, 6 Rue Coudenhove Kalergi, L-1359, Luxembourg

* Corresponding author. Tel.: +65-65500136 ; *E-mail address:* ahmed.qureshi@ncl.ac.uk

Abstract

This paper presents a stage based framework for analyzing transdisciplinary design processes in engineering product design and manufacturing. The framework provides a stage-wise, product lifecycle centric frame of reference for comparing design processes in industries from different industrial sectors involving multi-disciplinary stakeholders. The framework is based on extensive literature analysis in the domain of design theory and methodology, as well as from models in product life cycle management. The paper also reports insights on application of the framework for design processes analysis of 23 industries based on the mapping of their individual design processes to the developed framework.

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Keywords: Design Methodology, Design Stages, Product Lifecycle, Trans-disciplinary design, design processes

1. Introduction

Integrated product design and development in today's highly competitive, demanding and economically challenging world is a complex process that depends 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 intervention of expertise from different disciplines all along the product's lifecycle [1]. Comprehensive knowledge of a product's lifecycle is critical for experts involved in the design of the products as their decisions impact the downstream phases of the product life cycle, affecting other stakeholders.

Design methodologies and processes enable the designers to structure and carry out the tasks related to design, and are focused on the design and development phase of a product. The design activities and decisions carried out in the design phase rely heavily on the other phases in the product lifecycle. However, currently, these, and concepts of product lifecycle and lifecycle management have been developed in parallel without sufficient integration. The result is a limited overview of the downstream phases of the product lifecycle in design as well as an intuitive approach towards design, deployment, delivery, operation and support rather than a more systematic approach.

The narrow focus of product lifecycle focused support with respect to the available academic literature on design methodologies as well as trans-disciplinary design processes in organizations highlights the need of better understanding and integrating the issues related to trans-disciplinary design processes in the product lifecycle concepts and vice versa. The limited inclusion of the design methodology support in the product lifecycle management (PLM) models leads to overlooking aspects of product design with implications across its lifecycle. Often these implications are very expensive to overcome for the stakeholders. Addressing trans-disciplinary issues necessitates a holistic overview of the product lifecycle, incorporating not only discipline-specific tools and processes, but also transdisciplinarity and consideration of all the stakeholders.

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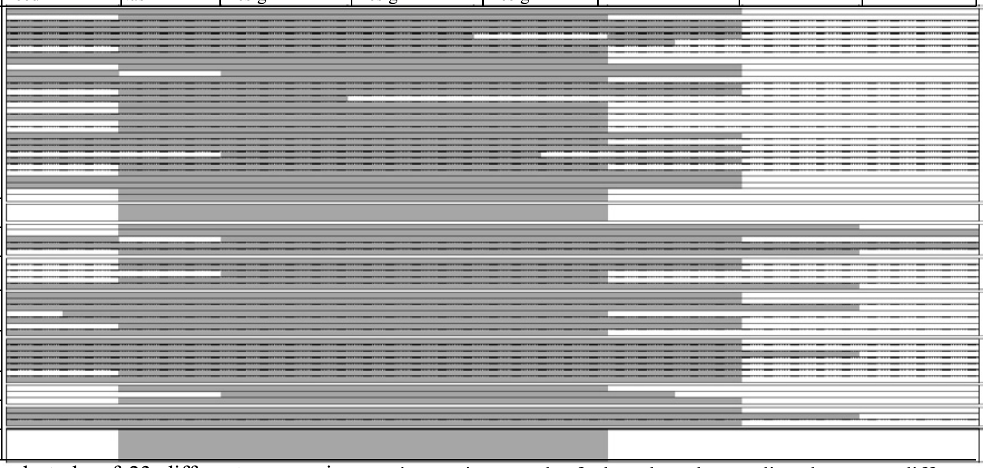
Table 1 Comparison of stages in design process models as per [2]

	Establishing a need	Analysis of task	Conceptual Design	Embodiment Design	Detailed Design	Implementation	Use	Closeout
Mechanical Engineering (n=31)								
Industrial Engg. (n=1)								
Systems Engineering (n=5)								
Building /Architecture (n=5)								
Software Design (n=7)								
Service Design (n=7)								
Mechatronics (n=3)								
PSS (n=3)								
Transdisciplinary (n=1)								



Based on an empirical study of 23 different companies, representing trans-disciplinary design and product development practice, this paper presents insights into the current state of the product lifecycle phases and stages considered by industry in the engineering product sector from a design process perspective.

The paper proposes a product lifecycle centric, trans-disciplinary, literature based, stage-wise product lifecycle for comparing the design processes and product lifecycles in various industrial sectors involved in design, manufacturing/production and sales/distribution of engineering products. A trans-disciplinary phase/stage based product lifecycle based on the empirical study is presented along with most common design states used across the spectrum of the industries and their appropriate stage.

2. Design stages from a transdisciplinary perspective

The design, development and realization of increasingly integrated products, based on specialized technology from different disciplines (including disciplines within engineering domain as well as other such as social sciences, health, business and management etc.), poses significant challenges to collaboration, cooperation and communication in a diverse transdisciplinary design environment. These challenges are compounded by increasingly demanding users, increased environmental awareness, expanding original problem space to include several issues more explicitly such as user issues, environmental issues, increased product functionality and complexity [3,4].

A vast number of prescriptive or descriptive design methodologies and process models from different disciplines have been proposed in the literature. Using domain specific terminologies, these methodologies and models provide support to the designers in carrying out the design process via stage based design process models. Majority of the process models propose stages at a varying level of abstraction of the design process while using different terminologies. The differences come from extent of the design process considered, engineering domain, product type, author's perspective as well as experience. However, with an increasing need of shared understanding between different disciplines, there is a need to analyze the existing literature for consolidating the commonalities across the existing design support.

In order to compare the design support from various disciplines, at a high level of abstraction, a holistic transdisciplinary overview of the design process stages in design methodologies, as well as design processes as practiced in industries is required. This overview is necessary to establish a common frame of reference that can be understood and implemented in a transdisciplinary context. In order to do so, the following subsections discuss the two fundamental perspectives towards the stage based description of the product lifecycle. i.e. from design theory and methodology literature as well as from PLM literature. In order to provide a consistent terminology for a comparison of process models the definitions provided in [5] are used distinguish between stages (often called design phases), activities and strategies.

2.1. Stages in design theory and methodology 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 design process models, thus contributed to a consolidation. Howard et al. [6] analyzed 23 process models mainly from mechanical engineering. They identified the following set of typical design stages: *establishing a need, analysis of task, conceptual design, embodiment design, detailed design, and implementation.* An overview and consolidation of existing comparisons of design methodologies & process models is provided in [4].

Table 2 Comparison of stages in PLM models

No.	Authors	Stages	Establishing a need	Design	Implement/Realize	Use/ Support	End of Life
1	Nosenzo [7]	4		■	■		
2	Sudarsan [8]	4	■	■	■	■	
3	Ameri [9]	5		■	■	■	■
4	Stark [10]	5	■	■	■	■	■
5	Liu [11]	6		■	■	■	■
6	Eigner [12]	7	■	■	■	■	■
7	Richuri [13]	9	■	■	■	■	■
8	Iyer [14]	5	■	■	■	■	
9	Corallo [15]	4		■	■	■	■
10	Kiritsis [16]	4		■	■	■	■
11	Kovacs [17]	6		■	■	■	
12	Rangan [18]	7	■	■	■	■	■
13	Ding [19]	7	■	■	■	■	■
14	Li [20]	7		■	■	■	
15	Hines [21]	6	■	■	■	■	
16	Cimdata [22]	4	■	■	■	■	
17	Amann [23]	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.

In another literature study, Gericke & Blessing [2] (Table 1) 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.

Eisenbart et al. [24] 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. 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 [25]. 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, conceptualization, preliminary layout, layout, and production documents*.

The above analyses provide a transdisciplinary over view of the product lifecycle as described and documented in the design theory and methodology literature. These can be used as a common lifecycle based reference for analyzing design in a transdisciplinary context. However, in order to have a more holistic view, it is necessary to augment this perspective by a comparison to the concepts of product lifecycle in the product lifecycle management (PLM) literature. This is presented in the following subsection.

2.2. Stages in Product lifecycle management literature

Product Life-Cycle Management (PLM) is a strategic business approach that consistently manages all life-cycle phases of a product, commencing with market requirements through to disposal and recycling [26]. CIMdata [23] defines the overall product lifecycle as comprised of three major, interacting lifecycles: Product Definition; Production Definition; and Operational Support. Stark [10] defines PLM as the activity of managing a company's products all the way across their lifecycles in the most effective way. Schuh et al [27] and Nosenzo [7] define PLM as a systematic concept for the integrated management of all product related information , processes and resources through the entire lifecycle, from the initial idea to end-of-life with the aim to overcome existing organizational barriers and streamline the value creation chain. Contrary to the popular perception of PLM being an IT based tool, PLM is a concept, not an IT system [28].

The PLM is not just computer technology, but rather an integrated approach, based on a set of technologies (CAD / CAE / CAM) and on defining processes [7]. The general perception of PLM however remains inappropriately tied only to that of a PLM system, which is a tool (an information system) that facilitates all or some subsets of PLM activities [10].

Based on a non-exhaustive literature review of popular research in last 15 years (1998-2013), from the fields of engineering, computer science, and business and management, on the keywords of 'lifecycle', 'PLM', 'product lifecycle', and 'design', a survey of stages of the product in product lifecycle as proposed by these publications was carried out.

Based on the literature review, Table 2 presents a comparison of the stages in PLM literature. Different authors break down the product lifecycle stages from a minimum of 4 to a maximum of 9 stages. By analysis of the individual product lifecycle models (n=17), as proposed in the literature, with respect to the comparison of Gericke et al. [2], and with other product lifecycle models, a common set of stages can be derived which is*: establishing a need, design, implement/realize, Use/Support, End of life*. The general description of these stages as adapted from [2] is given as follows:

- **Establishing a need:** initiation of the design process by a product idea, or the identification of a need or a problem
- **Design:** design and development of the product starting from initial description of the task/product idea to development of conceptual solutions, detailing of conceptual solutions, and to refinement and finalization of the solution.
- **Implement/realize:** Integration, manufacturing, installation, test approval and launch of the product
- **Use/support:** operation, monitoring, maintenance of the product
- **End of Life:** Recycling, disposal, update/evolution of the product

The review of the PLM literature reveals that most of the models (n=16) include three stages of *design, implement/realize,* and *use/support.* Around half (n=10) include the early stage of establishing a need, followed by (n=9) including the end of life stage. The PLM models cover more aspects of the products' life cycle in terms of the considered stages than models analyzed in the design theory and methodology literature.

A number of product lifecycle models presented in the PLM literature are adapted or inspired from the literature in the design theory and methodology e.g. ([18,29,30] vs ([3]). A comparison of Table 1 & Table 2 also reveals a difference in level of abstraction between the description of stages in the literature on design theory and PLM. Due to be being design centric, the models from the design theory are more detailed in the design stages, i.e. the description of the different parts of the design are treated as different stages within the product lifecycle as opposed to the PLM based model, which considers 'Design' to be a stage comprising the sub-stages that can be distinguished at a more detailed level of abstraction. Based on the above, the following section proposes a common framework for analyzing transdisciplinary design processes in engineering product manufacturing industry.

3. Common framework for transdisciplinary design

Analysis of design processes from a transdisciplinary perspective requires analyzing design processes for transdisciplinary products, which are designed and developed in organizations with transdisciplinary capabilities. This is a complex problem characterized by the fact that most of the organizations use specific terminology in their design processes. This is further complicated by different disciplines using discipline specific terminology. It causes difficulty in comparing the design processes within and among different industries. In order to address this difficulty, and to form a common frame of reference, to which different perspectives in the industrial design process may be linked, a framework based on analyses of the product lifecycle stages as summarized in Table 1 & Table 2 along with the transdisciplinary design states as provided in [24] has been developed.

Table 3 shows the stage view of the developed framework. It is based on a two tier stage model, from the consolidation of Table 1& Table 2. The stages divide the product lifecycle of the product in 5 stages. In order to gain more insight and details into the organizations' life cycle coverage and to develop a transdisciplinary basis for the comparison at a higer detail, each of the product lifecycle stages (with exception of the last phase) is subdivided into four main subdivisions. These were selected from the models analyzed in [2] and considered PLM literature representing major activities/stages in each particular phase. Each sub stage is then mapped to the transdisciplinary design states, giving the capability to capture of common design states in each sub-stage.

Table 3 Common transdisciplinary framework

Stages	Sub-Stages	Design States		
Establishing a need	Market Analysis and Forecasting	DS1	DS2	DS3
	Identification of Need			
	Project Management			
	Requirements specification			
Design	Conceptual Design			
	Embodiment Design			
	Detailed Design			
	Production Systems Development			
Implement / realize	Manufacturing			
	Assembly			
	Systems Integration			
	Procurement			
Use/ Support	Sales and Distribution			
	Installation			
	Operation			
	Service and Maintenance			
End of life	Retire/Dispose/Closeout			

4. Application to transdisciplinary analysis in industry

The developed framework was used as a central frame of reference in a transdisciplinary industrial study [31] comprising 23 representative design and manufacturing organizations for analysis of current product development and design practice. It was a part of a larger semi-structured questionnaire comprising 87 questions, available in a web-based format as well as in paper form. The questionnaire covered the 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 was representative for the organization. The expected results of the study was to evaluate if a common transdisciplinary design process can be consolidated from study of these organizations' design processes.

4.1. Industrial profile of organizations

The participants interviewed belong to organizations from 10 different countries. The participants were based in 14 different countries on four continents. 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.

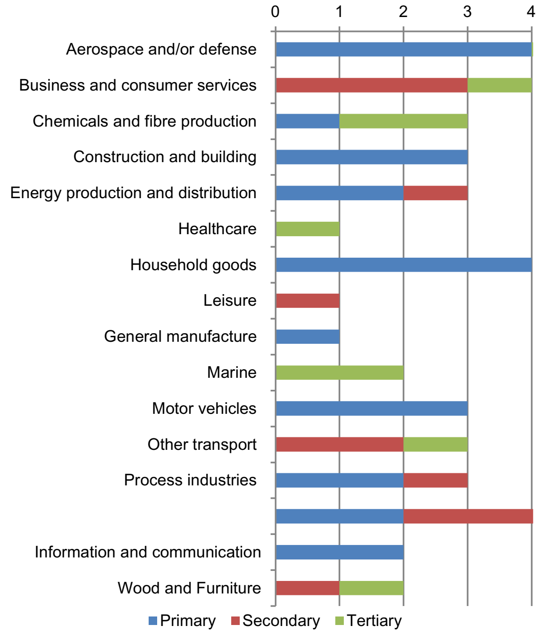


Figure 1 Industrial areas covered by the analyzed organizations

4.2. Interviewee details

The participants had a mean experience of 12.3 years in their respective fields. More than half (n=15) of the participants interviewed held hierarchical roles related to middle or upper management (project lead, corporate or executive manager) as opposed to technical specialists.

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

4.3. Results

22 out of 23 participants were successfully able to map the stages in their company specific processes to the proposed framework with no or little help (Figure 2). A majority (n=14) divided their organization's process into 4 to 6 stages. They then mapped these stages to the framework stages. The mapping exercise took into account the organizational processes, documentation as well as experience feedback from reference projects.

The participants were also able to map the sub-stages of their organizational processes to the sub-stages proposed in the framework. The mapping of the organizations' Stages and sub-stages was done by the participants themselves supported by the interviewer and detailed descriptions of the particular stages. All the participants reported that the 'establishing the need' and 'design' stages are covered. Most organizations (n=21) cover the 'implementation' stage. 17 cover the 'use' phase and 12 the 'end of life services'.

The participants further detailed sub-stages of each stage by mapping their specific sub-stages or activities to the sub-stages defined in the framework. They 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).

For each sub stage defined, the participants were able to assign the design states created, used or modified in that specific sub-stage. . 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).

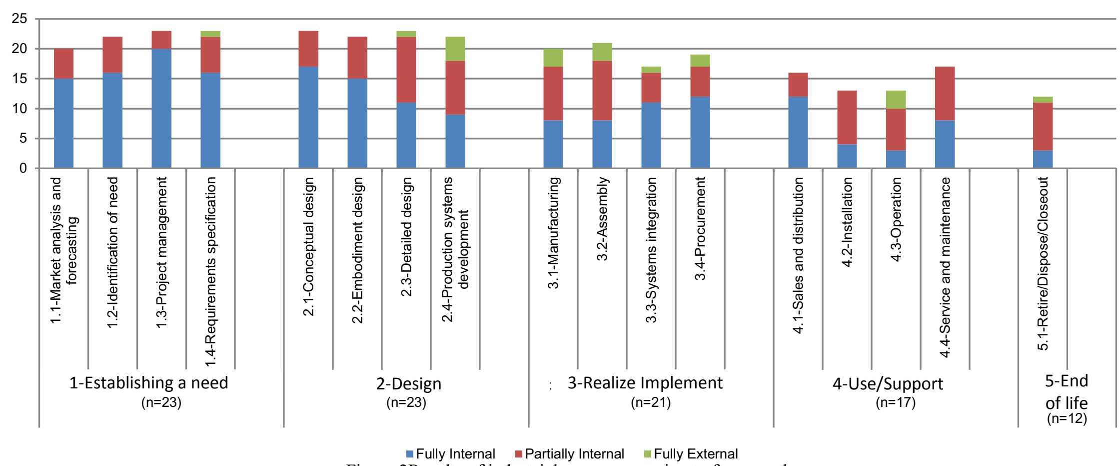


Figure 2Results of industrial process mapping to framework

5. Conclusion

The framework presented in this paper was mainly developed as a support to enable comparison of design processes in industries from different product types. This was done on the basis of extensive literature review to ensure that different disciplines as well as two import viewpoints of design theory and product lifecycle are considered. During the empirical study the framework was successfully tested at different levels of abstraction (across organizations within organization, project specific basis) in the industry.

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 developed framework. This is partly due to the fact that most of the interviewed organizations used a product lifecycle centric approach, making it easier to map the processes to the developed framework.

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 for describing and coupling the discipline-specific processes in specific industries.

The literature studies carried out for developing the framework also reveal the commonalities between the stage based nature of the models in PLM as well as the models in design theory and methodology literature. Both the models consist of a common set of stages. However, the models in design methodology lack focus on the later stages of the product lifecycle. The models in PLM consider the later phases more often but the main focus of the PLM remains to be that of information management with limited support for design processes as commonly found in design process models.

In the context of modern integrated transdisciplinary design and development, there is a pressing need for a common platform that enables integrated design, development design and management. Starting from a collection of tools, the PLM has moved to from being data and technology focused to being function focused, process focused and 'Bottom Line' focused. [23]. Inclusion and integration of design process support is however still very much limited. This can be improved by integrating the popular design methodology support (descriptive or prescriptive) in the PLM platforms that can then be understood in by different stakeholders of a transdisciplinary design project with minimum effort.

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