Transdisciplinarity and the Future of Engineering
B.R. Moser et al. (Eds.)

doi:10.3233/ATDE220702

Engineering Tools as Boundary Objects Between Product Development and Production

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Abstract. Product realization, i.e., product development and production, involves several transdisciplinary activities. People from different disciplines are involved, representing different practices and knowledge areas. These differences create boundaries, which must be crossed to succeed with the endeavor of product realization. One way of crossing boundaries is through boundary objects, i.e., artefacts that create common understanding between different domains. Boundary objects have been applied in for example educational research and are a promising approach in engineering. Between product development and production, engineering tools such as prototypes, simulation, and design for assembly are often used as boundary objects. Previous research has shown that different aspects affect whether an artefact function as a boundary object or not. However, the context of product realization remains unexplored in this topic. This paper, therefore, explores what aspects affect how an engineering tool can function as a boundary object. Based on a literature review, workshops and a case study, the paper presents aspects related to the situation, the tool and the individuals that affect it an engineering tool function as boundary objects. The paper addresses two important transdisciplinary concerns: knowledge from different disciplines is combined, and both academic and scientific goals are considered.

Keywords. Knowledge management, boundary crossing, boundary objects, case study, transdisciplinary engineering

Introduction

In the product realization process, product development and production are essential activities, typically carried out by different functions. Each function accumulates specialized knowledge related to its area that the other functions do not necessarily possess [1]. The success of the product realization process depends on the integrated outcomes from the different functions rather than the performance of the individual functions [2]. Thus, we need to manage knowledge between the different functions involved in the product realization process to successfully develop products that meet both the product and production requirements. However, knowledge integration, or managing knowledge across functions, can be challenging. The reason is that between the different functions, representing different knowledge domains, knowledge boundaries arise [2]. A boundary can be described based on its character, and as

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suggested by Carlile, it can be syntactic, semantic, or pragmatic [2]. Another suggestion is to distinguish between individual, domain-specific, task-specific, spatial, and temporal knowledge boundaries [3]. One way of managing knowledge across boundaries is through the use of boundary objects, objects that both inhabit several intersecting social worlds, and has the capability to satisfy the informational need in all of them [4].

Boundary objects have previously been applied in areas such as educational research [5], software development [6], agile systems engineering [7], and healthcare [8] and are gaining interest in engineering [9]. Boundary objects are contextual and dependent on the situation and what they need to convey, such as time perspectives or representations of data [4]. Because of this, a challenge is that an artefact may function as a boundary object in one situation, but not in another [10]. It can even have a negative effect if not sufficiently matched with the situation [11] and the boundary being crossed [12]. The question then arises: what makes an artefact function as a boundary object? Previous research has discussed different properties that affect how an artefact function as a boundary object [13]. Other factors affecting the usage of boundary objects, such as the situation it is used in [11], where it is used [14], culture [6], and political incentives [15] have also been discussed. Consequently, there exist several aspects that affect whether an artefact functions as a boundary object.

In product realisation, engineers use methods and tools such as computer-aided design (CAD), failure mode effect analysis (FMEA), prototypes, drawings, and others to support their work. These engineering tools have the potential to support knowledge integration between functions, representing different knowledge domains [2]. Transdisciplinary alignment is a critical aspect of transdisciplinary engineering [16]. If used correctly, engineering tools can function as boundary objects, and if not, they can instead become "*boundary roadblocks*" [10]. However, an understanding of what is required for these engineering tools to function as boundary objects remains undefined.

Hence, the purpose of the research presented in this paper is to identify what aspects affect whether an engineering tool function as a boundary object or not. This paper adds knowledge related to boundary objects and puts forward important aspects for engineering tools to function as boundary objects in the context of product realisation.

1. Managing knowledge across boundaries and boundary objects

Prior research has outlined several important lessons for managing knowledge across boundaries. The situation and the involved individuals, the design of a boundary object and its properties, as well as the match between the boundary object's capacity and the type of the knowledge boundary, play part in managing knowledge across boundaries.

Carlile discusses that boundary objects have different capacities and that their effectiveness depends on the match between the object's capacity and the type of boundary that needs to be crossed [10]. When a syntactic type of boundary exists, then there is a need to establish a shared syntax or language for individuals to represent their knowledge, such as repositories and databases. Examples of repositories are cost databases or parts libraries that provide a common reference point and shared values for problem-solving across domains. Boundary objects also have the capacity to reconcile different meanings to cross a semantic boundary. In that case, the boundary object needs to provide concrete means for the individuals to translate and learn about their differences and dependencies across the specialized domains[2][9]. Examples of boundary objects that can effectively deal with such a boundary are standardized forms and methods such as engineering change formats like design failure mode and effect analysis (D-FMEA), process failure mode and effect analysis (P-FMEA). These are shared formats for solving problems, with which structure individuals across the domains are familiar. Drawings, prototypes, mock-ups, computer simulations are considered objects or models that are a simple or complex representation that can be observed. They have the capacity to represent, learn, and transform knowledge and hence cross pragmatic boundaries when negotiation of interest across domains is required. The tangibility of prototypes for example allows the object to easily specify relationships among parts and dependencies among functions [10], [22].

Some researchers discuss that the situation itself and the involved individuals can affect the management of knowledge across a boundary. For example, Wenger argues that for a situation to support knowledge management it is required to have, among others, common ground, and mutual activity around which individuals from the specialized domains can gather around [11]. Individuals' open commitment and willingness to cross a boundary and reach out to others' competencies are enablers for knowledge management across a boundary.

In addition to the enablers that originate from the situation itself and the individuals, authors also discuss properties that an object needs to possess to serve as a boundary object and support knowledge management across a boundary. Star and Griesmer suggest that an object needs to *first*, support an efficient collaborative work relation, stimulate conversations and discussions; *second*, has a common structure that different domain specialists are familiar with and can relate to [23]. To function as a boundary object, it is required that the object has a mediational quality providing shared space between individuals from different domains; *third* has interpretive flexibility to provide room for the domain specialists to use and adjust the object to their local needs. *Fourth*, an object needs to allow for interaction with it and becomes a subject of reflection [23], [24]. Other authors (e.g., [7], [13]) further elaborate on, adds on, and even concretises the properties presented by Star & Griesmer [23]. Previous research [13] has highlighted such properties of an boundary object as; (1) *modularity* refers to the fact that an object is designed in a modular way and provides the domain specialists with the possibility to use part of an object without interfering with the other parts; (2) *abstraction* refers to an object designed in a way that includes general, common, and abstract principles to stress the commonalities across the specialized domains; (3) *concreteness* is related to the *interpretive flexibility*, which is also discussed by Star where the object's design allows a domain specialist to specify certain concerns and communicate knowledge related to a specific problem [24]; (4) *shared syntax* refers to the fact that an object needs to have a common syntax used and known across the specialized domains; (5) *malleability* refers to the property of an object that is easy to modify; (6) *visualisation* is an important property of a boundary object that adds graphical elements as a support to verbal and text communication; (7) *annotation*, as also discussed by Wlazlak et al, can further provide specific context for a local use [25]; (8) *versioning* refers to the property that can allow for tracing of changes made to an object including the rationales for those changes; (9) *accessibility* refers to making an boundary object known and available for individuals across specialized domains through for example different communication channels, and to provide know-how on using the object; (10) *up-to-dateness* refers to the fact that the object needs to be up to date, which is also discussed by Bechky in the context of new product introduction [26]. (11) *stability* refers to the property that requires that the core of a boundary object remain stable over time; (12) *participation* refers to the involvement of individuals across domains not only in creation but also in the administration and maintenance of the boundary object.

2. Method and material

The results presented in this paper were derived as part of a research project focusing on boundary crossing and boundary objects in the context of product realisation [17]. The research project follows an interactive research logic, which means that the academic researchers and the industrial partners work closely together during the entire research process[13][14]. The interactive research logic implies that practitioners and researchers jointly both formulate the problem and develop solutions [20], which is an essential element of transdisciplinary engineering [16].

The research project included several different activities. In this paper, results from two workshops and one case study are reported. A joint arena for learning is an essential element in a research project guided by interactive research [19]. In this research project, we have developed a workshop format labelled knowledge sharing sessions, referring to the purpose of the workshop. In total six industrial partners were involved in the research project, of which five were included in this study. An overview of the included companies in this paper is presented in **Table 1.** Overview of companies. Four of the companies participated in the knowledge sharing sessions. The three workshops, relevant for this paper, focused on the possibility of the engineering tools Design for X (e.g., assembly, manufacturing) (DfX) and Product Lifecycle Management (PLM) to function as boundary objects as well as a general workshop on what is required for something to function as a boundary object, which was used to verify the results of the findings in the paper.

Table 1. Overview of companies.

Company	**Transportation**	**Outdoor**	**Housing**	**Infohub**	**Armature**
Industry	Products for sport/outdoor and transportation	Engine-powered products for outdoor	Industrialized house building	PLM provider	Lighting armatures for indoor and outdoor use

The case study was carried out at one of the participating companies, Company Armature. The unit of analysis was the use of engineering tools in the context of their product realisation process [21]. In total 20 interviews were carried out via Teams, recorded and transcribed verbatim. The respondents were product owners, production managers, R&D manager, industrialisation manager, project office manager, project managers, engineering designers, production engineers, quality manager and test office manager. The interviews followed a semi-structured interview guide and specific questions were posed related to whether different engineering tools supported joint understanding. Follow up questions were posed to understand what was important for the tools mentioned to support joint understanding and thus function as boundary objects. The results from the transcripts were categorized based on the engineering tools mentioned. Descriptions of the situations when the tool was used and their perceived usefulness as boundary objects were compiled. The results from the interviews were discussed with the respondents and verified at a workshop.

3. Empirical Result

3.1. DfX as a boundary object

In the workshop on DFX, Company Transportation worked with Design For Assembly, Manufacturing, Standard, Platform, and Environment and had defined in their product realization process where DFX was included. It was owned by production and was based in Excel and consisted of a set of questions that had to be answered and which resulted in a score on fulfilment of the different DFX-categories they had. They normally discussed the questions related to the whole product, but it could be beneficial to also discuss them on a component level. DFX had the potential to be used in different ways depending on when it was used. In the earlier phases of the product realization, questions could be discussed with the intent to manage knowledge between functions and to learn, whereas it could later be used as a checklist that could be used for verification purposes.

Company Outdoor worked with Design For Manufacturing, Assembly, Automated Assembly, Sustainability and Recycling and it was included in their product realization process. It was unclear as to who owned the DFX but production often took the lead in performing it, which entailed different parts. One part was related to performing education and informing regarding how the DFX was supposed to be carried out. Another part was design guidelines and rules that included good/bad examples that the design engineers could use. The guidelines could be both on a global level but also specific to the different plants. DFX also entailed a set of questions that were either made in excel or in a computer program for production development. Company outdoor used an index to determine how well the DFX work had been carried out, which included ratings and goals that were strived for. DFX could be performed on individual components but also on the entire product during workshops when prototyped were test-assembled.

In the general discussion, it was highlighted that where DFX was used, if it was sent between people via email, or if you met around a table and discussed affected its usage as a boundary object. Understanding the purpose of why DFX should be done affected the usage, and everyone must deem it important for it to function as a boundary object. Time pressure could cause the companies to skip steps in the DFX, especially towards the later stages of the product realization process, resulting in the usage of DFX changing. Furthermore, having a goal in terms of producibility in the DFX was deemed important.

3.2. PLM as a boundary object

In the workshop on PLM, Company Transportation put forward that PLM is a set of systems and not just a single tool. PLM could contain functions such as bill of materials (BOM), revision management, cad files, and different types of reports. It was highlighted that PLM could be seen as a business activity; a system built on several other systems. Thus, it could contain and connect different sources of information and reports from these systems. The structures could be built differently depending on who you are and what function you represent. An important feature was seen as PLM being able to provide a “single source of truth”, which refers to that the information you get out from it can be trusted and that everyone can use the same source.

Company Outdoor also put forward that PLM is bigger than just a single program. Like company transportation, company outdoor also used PLM to store different types of BOMs such as Manufacturing BOM. PLM was also used to store drawings and to track changes in products, and change requests were logged in the PLM system.

Company Housing didn't work with PLM explicitly, rather they integrated the information into CAD files and building information modelling (BIM), which plays a similar role to PLM in the construction industry. One aspect affecting its role as a boundary object was that when the information was provided affected the usage. For instance, since the information was mainly stored in the CAD files, it became accessible earlier on in the process rather than later when it was supposed to be used.

Company Infohub said that each underlying function in PLM could be used as a boundary object. They also said that using PLM means a change in working due to it being process-based; that you need to decide when you want to use/access what. Because of this, implementation of PLM could result in differences in perception of how you work being made explicit. PLM could be used to extract snapshots of how things looked at a specific moment, connecting to an important aspect being that you know the information provided is correct; a "*single source of truth*".

In the general discussion, it was highlighted that the right information, to the right person at the right time, was important for PLM to function as a boundary object. PLM could provide a graphical representation of complex sets of data that can be tailored to different users, and PLM could as such be used as a changeable boundary object that changes depending on who uses it.

3.3. Prototype as a boundary object

Several respondents mentioned how prototypes had helped in creating common understanding. Prototypes at company Armature were mainly used during test assemblies, but also during meetings related to industrialization and the design. The test assemblies could be performed either in the production or in the prototype workshop. If the test assembly took place in the production, participants had higher expectations of the design being closer to finalized. Similarly, it was pointed out that the purpose of the test assembly, connected to the phase in the product realisation process, was not always clear to all participants: "*The production might not always understand how early we are in the project, but they see it as any assembly. So they will judge it as a finalized design*". Consequently, this affected how well the prototypes could create common understanding.

It was highlighted by several respondents that the physical attribute of the prototype was important, saying that "*there are a lot of people who also need something physical to squeeze and feel to get an understanding*". One respondent exemplified that aspects such as whether or not something is hard to press on during assembly could be more easily communicated with something that is physical. Another attribute highlighted was that the prototype "*was real*" and not just something theoretical, which enabled verification and to see if something "*works in reality and not just in theory*". Further, understanding the size, material and design becomes easier when looking at a physical prototype. From the production's point of view, a physical prototype enabled them to give input on for instance placement of screws and to see whether their placement was suitable or not. "*When seeing something live, you can point, you can discuss around it*". Having something physical to discuss around enabled people to "*see* *the same thing and consequences",* which made it easier to understand how someone else was reasoning.

3.4. 3D CAD as a boundary object

Some respondents mentioned why 3D CAD was a good tool to create common understanding. A strength of using 3D CAD was to gain an understanding of the whole product and how it was constructed. This was enabled partly by the ability to cut and show cross-sections of the product, a quote related to this was that "*I can look at the different parts that affect me, see a little bit how it can be*". Geometric measurements could also be shown and presented easily. On the other hand, not everyone understands a CAD model in the same way: "*But not everyone can interpret a CAD model as we think it should be interpreted*". 3D CAD models could be more suitable in the early phases of the product realization process, since they could provide a truer representation of the design as compared to an early prototype.

4. Discussion

Based on previous research and empirical data, aspects related to the situation in which the boundary is being crossed, the tool used and the individuals using it can be identified, elaborated on hereafter.

Which boundary: As noted by Carlile, the match between the artefact and the boundary being crossed is integral [10]. Related to the three categories of boundary objects presented by Carlile [10], the tools can be categorised as follow: PLM can be deemed as a repository since it can be used to retrieve information and documents. As stated earlier, PLM is more than just one tool, and the underlying functions themselves could function as boundary objects. However, as the underlying functions were not investigated in this research, PLM will be assessed as one tool used as a repository. DFX can be categorised as a method and finally, prototypes and 3D CAD can be deemed as objects and models. Consequently, they have the possibility to function as boundary objects across syntactic, semantic, and pragmatic boundaries. Each of these tools possesses properties that were identified for each tool based on the empirical data [13]. The properties identified for the different tools and the connections between the engineering tools and boundaries presented by Carlile are summarised in **Table 2.** Connection between boundaries, engineering tools and properties.

Table 2. Connection between boundaries, engineering tools and properties.

Boundary	Engineering tool	Properties
Syntactic	PLM	Modularity, Abstraction, Concreteness, Annotation, Versioning, Shared syntax, Accessibility, Up-to-dateness
Semantic	DFX	Concreteness, Annotation, Visualization, Participation
Pragmatic	Prototypes, 3D CAD	Modularity, Abstraction, Concreteness, Malleability, Stability, Visualization

Who is using it: as was seen in previous research [11] the people involved need to have common ground, mutual activity, open commitment and willingness and it can further be affected by culture [6] and political incentives [15]. Related to DFX, it was pointed out that the individuals doing the DFX had to deem it important, connecting to an open commitment as well as willingness to create common understanding. This was further emphasized during the verification of the results as an integral aspect from the individuals from both product development and production.

Why it is used: Previous research has mentioned that know-how in relation to accessibility is important [13]. However, as seen in the case of DFX and prototypes, the know-why was also important. For instance, if not everyone believed that it was important to perform the DFX, it could end up being more of a checklist rather than a boundary object that supported discussions. Similarly, it was pointed out that test assemblies of prototypes were affected by how well the participants understood the purpose. For instance, if the production thought that the product was close to being finished, they would judge it as such, which in return could hinder creating common understanding. Thus, understanding the purpose of a certain tool becomes important.

When it is used: As mentioned in previous research [3][9], managing knowledge is affected by temporality. This could be noted in relation to PLM, where the information it could provide and its ability to function as a boundary object was affected by when in the process certain information was needed. The test assemblies were reliant on the users understanding when in the process it was performed. This temporal requirement was also seen related to DFX, which could be used in different ways in different phases of the product realisation process. For instance, when the DFX was used closer to the end of the product realisation process when deadlines were approaching, the time pressure could result in steps being skipped, thus altering the tool and subsequently its ability to function as a boundary object. Another example of temporality was that a 3D CAD model could be used better in the earlier stages of the process as compared to a prototype due to the limitations in providing a correct enough prototype in such a stage.

Where it is used: Previous research has discussed the importance of where the managing of knowledge takes place [14]. Similarly, from the empirical examples related to DFX and Prototypes, it was noted that the place in which the engineering tool was used mattered. In the case of DFX, it was possible to use it only via email or to meet around a table. Related to the use of prototypes, it was highlighted whether the test assemblies were carried out in the production and the prototype workshop affected how the different functions perceived it. Thus, where the tool is used affects its function.

The aspects identified can be divided into three parts: the situation, the tool and the individuals using it, summarized in Figure 1. In the situation one needs to consider where, when and who is using the tool, as well as the boundary being crossed. The individuals using is need common ground, mutual activity, and willingness to cross the boundary. Finally, the engineering tool possess different properties that affect its usage.

5. Conclusions

To connect to the purpose *"to identify what aspects affect whether an engineering tool function as a boundary object or not*", we have identified aspects related to the situation, the tool and the individuals that affect whether an engineering tool functions as a boundary object. The findings were summarized in Figure 1, and by highlighting these different aspects, a greater understanding of engineering tools as boundary objects between product development and production is achieved. When taking these aspects into account, the successful management of knowledge across boundaries through the use of boundary objects can be supported.

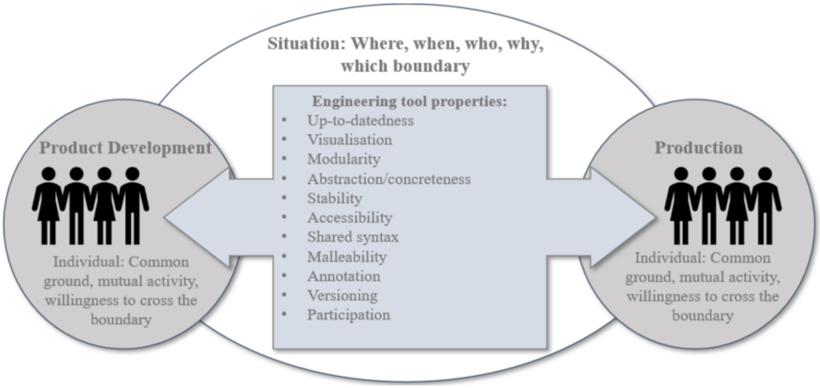

Figure 1. Aspects affecting if an engineering tool function as a boundary object.

Acknowledgements

We would like to thank our fellow researchers in the research project and the companies involved in the data collection. This research was financed by the Knowledge Foundation.

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