SPS2022
A.H.C. Ng et al. (Eds.)

doi:10.3233/ATDE220200

Knowledge Integration in Product and Production Development Through Boundary Objects and Additive Manufacturing

Paraskeva WLAZLAK[a,1] and Milad ASHOUR POUR[a]

[a] *Department of Industrial Product development, Production and Design Jönköping University*

Abstract. This paper discusses the role of prototypes with special focus on rapid prototyping or also called additive manufacturing. The authors of the paper combine literature on additive manufacturing and boundary crossing to increase the understanding about prototypes and specifically rapid prototyping during new product development. This paper is cross-disciplinary and aims to fulfil three objectives: (1) Synthesis of literature regarding potential role of prototypes to support crossing of the knowledge boundaries during new product development; (2) Outline of prototypes' properties that enable them to become boundary objects; (3) Outline meeting points between boundary crossing literature and the literature on additive manufacturing which can provide guideline for further investigation. The authors have found that the concept of boundary objects is still underdeveloped in the context of additive manufacturing, as the main benefits are related to quality, time, and cost. Through combination with literature on boundary objects, the role of prototypes to converge different diverging perspectives, translate and transform knowledge are emphasized and underlined.

Keywords. Prototype, Boundary Object, Additive Manufacturing, Product Development

1. Introduction

Companies need ability to rapidly adapt products and production system to new requirements. Realising mutual adaptability in practice requires management of knowledge gap or the so-called boundary that often exists between actors from the product and production domains when involved in development of new products. A mean to support the management of knowledge across boundaries is through implementation of objects or artefacts. Boundary objects (BO) are means that have the capacity to establish a shared language (vocabulary), support knowledge translation, as

[1] Corresponding Author, E-mail: paraskeva.wlazlak@ju.se.

well as facilitate negotiations and transformation of common and domain-specific knowledge between product and production domains during product development process [1, 2].

In the new product development literature, the role of prototypes (physical and analytical) is discussed as support for communication, learning and integration between actors involved [3], as the focus has been on the principles for prototyping, benefits, as well as prototyping technologies. In the boundary crossing literature, prototypes are mentioned as having the potential to support crossing of knowledge boundaries between actors that have different specialization [2, 4]. However, the literature has been scattered as to the role of prototypes to support the meeting point between actors that belong to different specialized domains, as product and production development. Furthermore, literature dealing with boundary crossing and boundary objects suggests that boundary objects are contextual and are situation-dependent, which implies that one object can work in one situation, and it may not work in another.

To understand more about boundary objects and specifically understanding prototypes and their role to bridge knowledge boundaries during new product development, it is important to understand the situations (circumstances) in which they are used and what parameters prototypes possess. Hence, it will be beneficial to deepen our knowledge regarding prototypes and their role as boundary objects during new product development. One of the most recent technologies that has been used by industry to develop prototypes rapidly and speed up the process of new product development is additive manufacturing (AM) [5]. AM has been utilized in industry to overcome several constraints and enable new capabilities among which, fit and form testing [6], rapid prototype development [7], low volume productions [8], assembly consolidation [8], and weight reduction [9] can be named. Given AM's independence from tooling requirements and its shorter lead times compared with those of conventional manufacturing technologies, a prototype of the final product can be readily made by the product team and then passed on to the production for proof of product concept development. Testing the design, identification of potential areas for development prior to production tooling, and ensuring that concepts such as design for manufacturing have been properly observed during the design phase are some of the practical advantages that can be realized through prototyping.

1.1. Purpose and contribution

This paper is a cross-disciplinary study which reviews and synthesizes literature fields on boundary crossing and AM to fulfil the objective stated in this paper.

Answering the objects will help understand the role of prototypes to support knowledge management and boundary crossing during product development process. It will further help explore how boundary objects can facilitate flow of knowledge and relay diverging interpretations of a product between two different perspectives.

The objectives of this paper are:

- Synthesis of literature regarding potential role of prototypes to support crossing of the knowledge boundaries during new product development.
- Outline of prototypes' properties that enable them to become boundary objects.
- Outline meeting points between boundary crossing literature and the literature on AM which can provide guideline for further investigation.

1.2. Method and work organization

This study is considered as a rapid overview (see [10]). This includes synthesis of literature on boundary crossing and prototypes, as well as literature on additive manufacturing. The rapid review included assessment of what is already known about the role of prototypes from a boundary crossing perspective and connections that existed with the literature on additive manufacturing as a technology to develop prototypes. One of the hypotheses with which the authors of this paper started was if changing external factors (advances in manufacturing technologies) would support the role of prototypes to act as boundary objects. The databases to detect the paper were Scopus and Web of Science. The focus was on type of publications like scholarly journals and conferences. The key words were combination of *boundary objects, boundary crossing, product development, prototypes, and additive manufacturing*. The search outlined a number of papers which were then screened according to their abstracts for their relevance. For example, papers that were within the software engineering context were removed. The analysis of data was focused on the role of prototypes, prototypes internal properties as well as benefits of the prototypes. The summary of the outcomes of the analysis is presented in Table 1.

2. Knowledge boundaries in new product development

Specialized knowledge is important for companies to be able to adapt to the environment surrounding that company. At the same time, for an organization to be able to serve its overall purpose, the actors that have specialized knowledge need to be integrated [11]. New product development is a process that requires working across specialized knowledge domains [2], which typically are organized in different departments such as product development and production development. Taking the boundary crossing perspective, the fundamental idea is that specialization in different knowledge domains creates a knowledge gap or also called boundary between actors that belong to different knowledge domains. Boundaries between actors from different domains evolve owing to the nature of knowledge that includes knowledge difference, dependence, and novelty [1]. In this thread of thoughts, difference refers to the differences in the amount and type of knowledge that actors possess. Knowledge dependency refers to the fact that actors need to take each other into consideration if there are to perform and complete their development activities. Finally, knowledge novelty is related to how new a situation is and the lack of common ground or knowledge between different actors. The more the difference and dependencies increase, the knowledge boundary that exists between the actors also increases.

Three types of knowledge boundaries which may need to be crossed during new product development are suggested by [1], namely syntactic, semantic and pragmatic. Syntactic boundary (or information processing) implies that common knowledge and shared syntax about differences and dependencies between actors exist and managing this type of a boundary requires simply transfer of domain-specific knowledge [1]. This type of a boundary is not in focus in this study. Increasing the novelty leads to decrease of the amount of common knowledge and a semantic boundary (or interpretive boundary) occurs. Novelty makes some difference in the type of domain-specific knowledge (e.g., language, tools, methods) unclear and some meanings ambiguous. Crossing this type of boundary requires translation of knowledge and reaching mutual understanding, with other words it is important to establish shared vocabulary and common ground. Pragmatic boundary (or political boundary) is related to the fact that often actors are reluctant to alter their knowledge and to acquire new knowledge investments and effort are necessary. That is why, a situation can arise where actors need to negotiate their interests. Crossing this type of boundary would require not only knowledge translation process but also knowledge transformation where actors alter the existing knowledge and create new [1]. Visual representation of the type of boundaries and the associated knowledge management and boundary crossing processes (transfer, translation and transform) are shown on Figure 1.

Literature on boundary crossing puts forward that crossing knowledge boundaries between actors from specialized domains during new product development would require different objects that can help to cross different types of boundaries. Star's study explains that boundary objects can be concrete or abstract objects which are a form of communication between actors involved in a development effort [12]. According to [12] boundary object needs to be robust enough to maintain a common identity between parties, yet plastic enough to adapt to local needs and constraints of the actors that are using them. Using the Stars' definition of boundary objects, a design drawing is a boundary object that can be used to communicate design intent between actors involved in a product development.

Boundary objects have different capacity and properties that help them to become the support that is needed for crossing different types of boundaries [2, 13]. [2] argues that when a syntax is shared and stable (where the meaning of word is shared between actors) then the knowledge management process is associated with knowledge transfer. An example of an object that support knowledge transfer is a repository where difference in actors' knowledge and the dependencies between the actors are specified and known. Other boundary objects are needed when it comes to crossing semantic boundary. Example of such objects in the new product development context are standardized formats and methods such as design failure mode and effect analysis (D-FMEA). These are shared formats for solving problems, where the structure and the language are mutually understood. These boundary objects have the capacity to reconcile different meaning and to support a process called knowledge translation [4]. Furthermore, common boundary objects that can help crossing semantic boundary are sketches, drawings, prototypes, and simulations [2, 4]. Furthermore, objects have the capacity to help to negotiate interests and make trade-off between actors. The negotiation process includes explanation of the choices actors make (for example proposed design modifications). Boundary objects are not effective in every context and are dependent on the situation in which they are used.

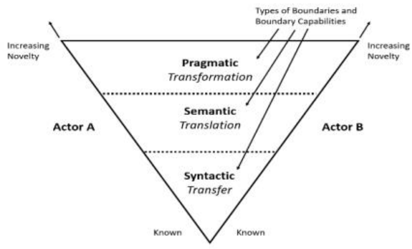

Figure 1. Type of boundaries and integration processes (based on [1])

3. Prototypes and their role as boundary objects

Developing prototypes is one of the most critical activities in the new product development [14-16], however, there are limited number of studies that investigate the prototypes and their role from a boundary crossing perspective. In the boundary crossing literature prototypes are discussed as having various purposes during the new product development process [17]. Prototypes are typically perceived as concrete means for translating and learning about the difference in type and dependencies between actors that are divided by a knowledge boundary [2, 13] The nature of the situation (or the problem) at hand is the one that steer what is adequate concreteness for a given boundary object. Physical prototypes are concrete objects that specify the relationship between parts and the dependencies between actors involved in the product development [3]. A conclusion drawn from the prior research is that tangibility of the physical parts allows easy specifying of differences and the dependencies between actors [1].

[15] explains that a prototype can have a several roles, for example to support communication, aid learning and informed decision-making. Moreover, according to according to BenMahmoud-Jouini and Midler [17] prototypes can support actors and are means for inspiration. Prototypes can support generation of new knowledge by recombining or transforming existing knowledge and support divergent thinking.

Within the role of prototypes to support communication, prototypes are described as having capacity to facilitate negotiations and reach consensus [16]. Further, prototypes can act as tools to persuade others about the design (explanation about a concept and enabling a feedback) [15, 17]. Taking the role of the prototype as a communication tool, simple prototypes can have a passive standalone representation (used a reference without direct interaction) or can be also considered as an active medium for discussion (physically interacted with by the actors). Prototypes' role to enhance communication is important to reduce the chance for miscommunication and avoid delays to the meeting by establishing a common ground [17]. Showing during meetings physical prototypes (or digital) is a way to create a common language or a mental model that is shared between the involved actors. A combination of verbal conversation and visual representation (by using a prototype) is a way to reduce the chance of confusion during technical explanations [15]. [17] argues that prototypes can be used to support communication by removing cultural and language barriers.

Prototypes support the meeting between actors representing different knowledge domains by creating similar mental model which would not being able to achieve during verbal conversations. The actors have different knowledge and the object (in that case the prototype) can help them to meet in the middle and convey their knowledge so that they can understand each other. Being able to translate knowledge by using prototypes can help take decisions which might not have been possible if prototypes were not in use. [15] is in line with [2] stating that once common ground or common understanding is established then the prototypes can be used for negotiation of design aspects and creation of new knowledge [17]. Prototypes can be used for both, to receive new information and to confirm already existing knowledge (understanding unknowns about the product). Building and testing prototypes help designers to obtain tacit knowledge regarding the product and hence make it possible to learn about known unknowns and even reveal unexpected aspects of the design (e.g., technical aspects including material costs and manufacturing) [3, 15, 17]. If the prototypes do not perform as intended, they can be reconstructed. Interacting with prototypes can aid obtaining of tacit knowledge (own understanding about technical aspects). The role of prototypes to catalyse learning is also discussed by [13, 17]

Using prototypes (either through referencing them or through interaction) can assists informed decision-making during new product development (e.g., taking decisions that lead to more feasible products). [17] argues that prototypes can support conversion of divergent thinking and support reflection on different ideas. This is in line with [18] who argues that prototypes help to reconcile different perspectives and that there is always a need to establish some cognitive link between actors that have different domains working on development of new products. Moreover, one of the properties that was proposed as important when establishing a common ground was the prototypes need to be malleable, i.e., adapt to adapt to different changes internal and external.

Table 1 presents summary of the literature regarding the role of prototypes from a boundary object perspective, including: (1) benefits of using prototypes; (2) role of prototypes during new product development; (3) prototypes' internal properties (that enable them to work as boundary objects).

Table 1. Summary of reviewed literature on boundary crossing

Benefits	Role of prototypes	Properties
Avoid misunderstandings (around technical aspects)	Facilitates negotiation (of design aspects) and managing tension between diverging viewpoints	Simplicity
Avoid delays to the meetings	Used to persuade others (explanations)	Tangibility
Avoid misinterpretations (confusion, metal burden)	Being a medium for discussion and enable rich conversations	Visual representation • Visualize mental ideas
Achieve feasible product designs	Used as standalone representation (reference)	Provide opportunity for testing
	Used to establish common ground (common language)	Being able to adapt/modify (malleable)
	Help to develop a mental model	Being combined with arenas for discussions (meetings)
	Help to obtain tacit knowledge	Provide concrete means (concreteness)
	Aid learning	Something that you can reference or interact with (it can be transformed)
	Assist informed decision-making	Being able to specify relations (dependencies)
	Used a mean for inspiration	
	Used to convey and translate knowledge	

4. Methods to develop prototypes

Creating prototypes in the process of new product development is a well-established practice [19]. While they are mostly used for design validation purposes, they can be characterized as conceptual, geometric, functional technical, and final prototypes [20]. A summary of applications for each type has been adapted in Table 2.

Creating prototypes in the process of new product development is well-established practice [19]. While they are mostly used for design validation purposes, they can be characterized as conceptual, geometric, functional technical, and final prototypes [20]. A summary of applications for each type has been adapted in Table 2.

Table 2. Different types of prototypes and their applications, adapted from [20]

Prototype	Application
Conceptual	Assessment of product and/or manufacturing concept
Geometric	Assessment of product and/or manufacturing geometry
Functional	Assessment of product and/or manufacturing functions
Technical	Pilot test of product/component and/or manufacturing/device
Final	Small batches

According to Canuto da Silva and Kaminski [20], physical prototypes can be developed either through conventional manufacturing technologies such as casting, forming, injection molding, or by using more recent technologies like rapid prototyping. The concept of physical prototypes are in contrary to the virtual prototype development where computer aided design (CAD) and computer aided engineering (CAE) are used to develop virtual prototypes. Rapid prototyping is another term to refer to AM in literature and industry. In comparison with other conventional technologies, there are some unique characteristics that make it stand out. While some of these were mentioned in the introduction chapter in this paper, it needs to be stated that prototyping has been one of the initial applications of AM in industry. The general drivers behind this are AM's capabilities to eliminate tool requirements, reduce material consumption, wastes, lead-time, and cost, while providing the opportunity to design complex shapes in qualities that are comparable to those of conventional technologies e.g., injection molding [21]. Despite the wide range of impacts that AM can cause from design to the manufacturing and even supply chain, there needs to be an emphasis on some key factors that are important in prototype development as it is one of the intended objectives of this paper. As it was mentioned earlier, prototype development is one of the core steps in development of new products. But this is easier said than done. To arrive at a clear understanding about a certain design of a product, all the people and departments that are involved in this process need to be able to communicate their requirements to one another. This would inevitably result in demanding and time-consuming discussions about important aspects of the product such as design, manufacturing processes, functionality, quality, etc. Any improvements in this process should result in a reduction of lengthy and frequent discussions that take place between product and production departments at the product concept development. The ability to have quick and efficient regular meetings with accurate and controllable outcomes will be the practical benefits of any such improvement effort. Another important aspect concerns cost of developing prototypes. Prototypes could not only undergo several modifications throughout the process, but the original design and concept might become completely overhauled at the end of the concept development phase. It is thus prudent to make the prototypes with careful cost considerations and avoid incurring expensive or unnecessary investments that could be wasted as the natural evolution of the product development progresses towards the final product. However, this attention to the cost should not come at the expense of quality. If anything, the prototype needs to demonstrate a crude estimation of how the final product will be, including functionality, geometrics, quality, etc. So, it can be argued that selection of the prototyping method needs to be made in a way to ensure certain requirements are met along the way i.e., rapid development of quality parts in a cost-efficient manner.

5. Discussion and Conclusion

When it comes to the integration of AM and BO in literature, the number of research papers published in this context is underwhelming. In one such example, the author presents a case study that explores the role of BO in two companies [22]. The first case is a cloud computing company which provides customer relationship management services for its users, and the second case is a network of companies that supply AM (3D printing) services. The study identifies a list of functions that BO plays in coordinating business relationships in physical and digital contexts, namely: simplification, stories transfer, socializing concepts, knowledge contextualization, engagement in a broader experience, and boosting creativity. This is considered to be only partly relevant to the subject of AM and BO, even though it is mainly concerned with the business aspects and not directly related to the use of AM or prototypes. Another more relevant study which is quite close to the intentions of the authors can be found in [23]. This paper explores iterative development of prototypes through AM as an interdisciplinary facilitator in the design and development of a modular hearing aid. The results of that study can be used to understand how a team made up of interdisciplinary skills can navigate through technical, social, and procedural issues in a controllable environment. As it seems, the concept of boundary objects is still underdeveloped in the context of AM. Still, and despite the distinctiveness of the fields, the authors believe there is a potential which can be seized from the synergy between AM and BO. The combination of BO and AM provides a great overview of the benefits in using physical prototypes especially those prototypes that are built with emerging technologies like AM. The benefits could be related to the cost, quality, and time advantages of AM over other prototyping methods. The role of the protypes as described in Table 1 (include but not limited to facilitating communication, learning and informed decision-making) could be facilitated by using prototypes developed with new manufacturing methos where the important prototype properties could be enhanced (like visual representation, easy, and fast to modify).

It is anticipated that various groups and individuals would be interested in the results of this research, chief among which would be product designers, production engineers, suppliers, and project managers. This is because while the overall value for a product under development is shared among all these groups, they tend to evaluate the product from perspectives which are not necessarily overlapping, thus, leading to diverging and even conflicting points of view.

Future research will be directed towards conducting literature review mapping the role of prototypes according to the stages of the development process and focusing on the boundaries that are crossed with the help of rapid prototyping. Perhaps, depending on the role of the prototypes during the new product development different properties could be in focus. This will help in exploring the role of prototypes during new product development, as well as the prototypes' own properties. In combination with this, the authors have the ambition to conduct an experiment including a practical application of AM for developing prototypes and then testing it in a real production environment. The authors remain to answer the question: would the use of new technology (as additive manufacturing) provide new properties to the prototypes and hence support their role to act as boundary objects during new product development. It is interesting to have more insights into how new technologies could influence the possibilities for different objects to acts as boundary objects. One such possibility that is provided by using rapid prototyping is supporting conversation during engineers' daily work as the prototypes can be changed rapidly reflecting feedback and concerns presented from different specialists. Furthermore, using rapid prototyping could facilitate verification of the design, manufacturing process, and quality aspects. Having a physical object during the new product development stage would not only visualize how different viewpoints could affect the final product's configuration, but help resolve conflicting aspects that could otherwise emerge at a later stage and consequently increase the overall cost of product development.

References

[1]. Carlile, P.R., Transferring, translating, and transforming: An integrative framework for managing knowledge across boundaries. Organization Science. 15(5): p. 555-568.

[2]. Carlile, P.R., A pragmatic view of knowledge and boundaries: Boundary objects in new product development. Organization Science. 13(4): p. 442-455.

[3]. Ulrich, K.T., M.C. Yang, and S.D. Eppinger, Product design and development. Seventh edition (international student edition) ed. 2020, New York, NY: McGraw-Hill Education.

[4]. Bechky, B.A., Sharing Meaning Across Occupational Communities: The Transformation of Understanding on a Production Floor. Organization science (Providence, R.I.), 2003. 14(3): p. 312-330.

[5]. Ngo, T.D., et al., Additive manufacturing (3D printing): A review of materials, methods, applications and challenges. Composites. Part B, Engineering, 2018. 143: p. 172-196.

[6]. Dehoff, R., et al., Case study: additive manufacturing of aerospace brackets. Advanced materials & processes, 2013. 171(3): p. 19.

[7]. Campbell, I., D. Bourell, and I. Gibson, Additive manufacturing: rapid prototyping comes of age. Rapid prototyping journal, 2012. 18(4): p. 255-258.

[8]. Huang, Y., et al., Additive Manufacturing: Current State, Future Potential, Gaps and Needs, and Recommendations. Journal of manufacturing science and engineering, 2015. 137(1).

[9]. Böckin, D. and A.-M. Tillman, Environmental assessment of additive manufacturing in the automotive industry. Journal of cleaner production, 2019. 226: p. 977-987.

[10]. Grant, M.J. and A. Booth, A typology of reviews: an analysis of 14 review types and associated methodologies. Health information and libraries journal, 2009. 26(2): p. 91-108.

[11]. Tell, F., et al., Managing knowledge integration across boundaries. First edition. ed. 2017, Oxford: Oxford University Press.

[12]. Star, S.L., Chapter 2 - The Structure of Ill-Structured Solutions: Boundary Objects and Heterogeneous Distributed Problem Solving, in Distributed Artificial Intelligence, L. Gasser and M.N. Huhns, Editors. 1989, Morgan Kaufmann: San Francisco (CA). p. 37-54.

[13]. Gustavsson, M. and K. Safsten, The Learning Potential of Boundary Crossing in the Context of Product Introduction. Vocations and Learning. 10(2): p. 235-252.

[14]. Lauff, C., et al., WHAT IS A PROTOTYPE? EMERGENT ROLES OF PROTOTYPES FROM EMPIRICAL WORK IN THREE DIVERSE COMPANIES. 2017.

[15]. Lauff, C.A., D. Kotys-Schwartz, and M.E. Rentschler, What is a Prototype? What are the Roles of Prototypes in Companies? Journal of Mechanical Design. 140(6).

[16]. Droz, D., Prototyping: A Key to Managing Product Development. The Journal of Business Strategy. 13(3): p. 34.

[17]. BenMahmoud-Jouini, S. and C. Midler, Unpacking the notion of prototype archetypes in the early phase of an innovation process. Creativity and Innovation Management. 29(1): p. 49-71.

[18]. Subrahmanian, E., et al., Boundary Objects and Prototypes at the Interfaces of Engineering Design. Computer Supported Cooperative Work. 12(2): p. 185-203.

[19]. Clark, K.B. and T. Fujimoto, Product development performance : strategy, organization, and management in the world auto industry. 1991, Boston, Mass: Harvard Business School Press.

[20]. Canuto da Silva, G. and P.C. Kaminski, Selection of virtual and physical prototypes in the product development process. International journal of advanced manufacturing technology, 2016. 84(5): p. 1513-1530.

[21]. Calignano, F., et al., Overview on Additive Manufacturing Technologies. Proceedings of the IEEE, 2017. 105(4): p. 593-612.

[22]. Corsaro, D., Crossing the boundary between physical and digital: the role of boundary objects. IMP Journal, 2018. 12(2): p. 216-236.

[23]. Heiss, L., Iterative Prototypes as 'Boundary Objects': Facilitating Interdisciplinary Collaboration of a Modular Hearing Aid. The Design journal, 2020. 23(6): p. 865-883.