INTERNATIONAL CONFERENCE ON ENGINEERING DESIGN, ICED23
24-28 JULY 2023, BORDEAUX, FRANCE

A BOUNDARY OBJECT FOR MAPPING, COMPARING, AND INTEGRATING PRODUCT DESIGN METHODS

Velleu, Jesse;
Brei, Diann;
Gonzalez, Richard;
Luntz, Jonathan

University of Michigan

ABSTRACT

There are innumerable design methods that exist across a wide spectrum of disciplines, ranging from engineering, to marketing, to psychology. However, the organic, multidisciplinary nature of methodological development in design leads to challenges in comparing or combining methods. Disciplinary perspectives can create conceptual 'boundaries' that may not align with the fluidity of the problems that designers may need to address. It is challenging to work between the boundaries of these design methods due to the unclear delimitation of exactly where and how methods may be integrated. Nomenclature is unstandardized and different terminologies may describe similar phenomena. To address this, a boundary object—the Actor-Abstraction matrix—is developed to recontextualize each of these divergent methods onto a common scale so they may be better understood in reference to their peers. A meta-analysis of four established design methods is performed to demonstrate the flexibility of this conceptual device. With this tool, existing design methods may be more easily examined to identify points of compatibility and gaps in their coverage, and could also serve as a powerful platform for the creation of new design methods in the future.

Keywords: Design methodology, Design theory, Embodiment design, Ontologies

Contact:
Velleu, Jesse Lucas
University of Michigan
United States of America
jvelleu@umich.edu

Cite this article: Velleu, J., Brei, D., Gonzalez, R., Luntz, J. (2023) 'A Boundary Object for Mapping, Comparing, and Integrating Product Design Methods', in *Proceedings of the International Conference on Engineering Design (ICED23),* Bordeaux, France, 24-28 July 2023. DOI:10.1017/pds.2023.4

1 INTRODUCTION

The creation of formal design methods is the foundational aim of both engineering design research (Blessing and Chakrabarti, 2009) and design science research (Gregory, 2014). A design method is a specification for how a design problem is formulated, what the inputs and outputs are, what tools may be used for modeling potential solutions, and what procedures are followed (Gerrike et al., 2017). Designers seek to define methods such they may be *formalized* and ultimately *generalized* (Cross, 2021). Design is a practice that encourages multidisciplinary or intersectional actions (Tharchen et al., 2020), and therefore variety of different disciplines participate in this process (Papalambros, 2015). The implication of this multidisciplinary formalization is that these design methods often become conceptual 'wrappers' for the underlying processes that they describe. These 'wrappers' contain the procedures, associated statistical or graphical tools, input/output designations, etc. (Gerrike et al., 2017), which are each built upon distinct taxonomical and/or ontological foundations.

In a vacuum, this divergent development may not be problematic. Design methods are typically developed to address specific problems (Gerrike et al., 2017), and are typically quite effective in these aims. The reality of design, however, is that the problems that designers must address do not always align one-to-one with the available design methods. In these instances, it can be desirable to combine or integrate multiple different design methods to better suit the problem at hand. Interest in understanding how different design methods can complement each other has been growing in recent years (Yannou et al., 2018). While this has been demonstrated to be possible in many cases, e.g., (Neto and Pires, 2020; Schütte, 2002; Wang, 2015), there is no clear delimitation of exactly which design methods may be integrated together and which cannot, as well where exactly their potential compatibility points may lie. Nomenclature is also unstandardized and practitioners may use different terminologies to describe similar phenomena (Gero and Kannengiesser, 2014; Tharchen et al., 2020). Critical concepts can also have divergent definitions (e.g., Al-Fedaghi, 2016). Working between the implicit *boundaries* imparted by the conceptual 'wrappers' of formalized methods is therefore a challenging proposition that highlights the issues of multidisciplinary formalization without any sort of higher-lever structural guidance.

To address this issue, a *boundary object* for product design methods is developed in this work. A 'boundary object' is the general term for a flexible formalization that may be used to span conceptual boundaries and link divergent perspectives or disciplines (Star and Griesemer, 1989). Boundary objects are commonly identified by three characteristics: 1) flexibility to adapt to different perspectives or problems, which is 2) achieved by defining an looser organizational structure that may then be more precisely formulated for specific problems, and 3) a resulting methodology that may be commonly employed by various practitioners who lack conceptual or taxonomical consensus (Star, 2010).

While some have considered the broad act of 'design' itself to be a sort of natural boundary object (Tharchen et al., 2020), this work aims to develop a more explicit tool that may be used to integrate previously formalized methods for design. A mechanism for bridging conceptual boundaries between formal design methods is needed to better understand which aspects of a design problem they do or do not address, and where they may be integrated with other methods or otherwise require extension. In this paper, a graphical boundary object called the *Actor-Abstraction (A-A) matrix* is developed. This boundary object aims to map each of these divergently developed design methods into a common frame of scale, such they may each be better understood in reference to each other.

A meta-analysis of four preeminent, *quantitative* design methods is preformed, in which each is mapped into the ontological structure provided by the A-A matrix. This includes Function-Behavior-Structure (FBS) (Gero, 1990), Quality Function Deployment (QFD) (Ramaswamy and Ulrich, 1993; Singh et al., 2018), Kansei Engineering (KE) (Nagamachi, 2016), and Conjoint Analysis (CA) (Green and Srinivasan, 1990). Each of these methods were selected as representatives of different disciplines or perspectives that participate in design, including engineering (FBS), project management (QFD), psychology (KE), and marketing (CA). None of these design methods are static. As they are used, they each continuously evolve and are formally extended to better meet the needs of different practitioners. These extensions alter how these methods are used and relate to each other. This meta-analysis exercise serves as a proof-of-concept for the success of A-A matrix as a boundary object, and allows for these design methods to be directly compared, and for their integration points to be identified. In the future, this tool may serve as a platform for extending these existing design methods or even building new design methods that are readily tailorable to specific design problems.

2 THE ACTOR-ABSTRACTION MATRIX

Each of the selected design methods defines various *spaces* within the design process (e.g., 'engineering characteristics,' 'properties space,' etc.) through the lens of their specific discipline. However, it can be unclear as to how terms like ‘engineering characteristics’ in QFD and the ‘properties space’ in KE relate to one another, or whether they are actually describing the same concepts. To compound this, definitions can shift over time and even tend to be modified on a case-by-case basis to fit practitioners’ specific needs. A boundary object therefore must provide a *general* structure that is capable of commonly supporting the *specific* perspectives of each of these methods. To do this, a graphical matrix—dubbed the Actor-Abstraction (A-A) matrix—is used to deconstruct any design method across two dimensions: *Actors* and *Abstractions*. Each of these dimensions may be then broken down into 3 levels, resulting in the 3×3 grid structure given in Figure 1, in which each cell represents a domain defined by the pairing of an Actor and an Abstraction level (e.g., Artifact-How, Context-What, User-Why, etc.).
The specific spaces defined in each design method (e.g., 'properties space') may be categorized by, and drawn into the cells of this matrix. This translates the method-specific terminology into a more general nomenclature (e.g., Artifact-What) that is better suited for multidisciplinary use. The matrix itself represents the *loose* organizational structure of this boundary object, as it is flexible enough to support each of these methods. *Precise* organizational structures may then be created by visually mapping specific design method into the matrix using the associated graphical notation given in Figure 1. Each of these dimensions, as well as the manner in which the graphical notation is applied, is first defined here in general terms. This is subsequently put into use to map out each of the four example design methods.

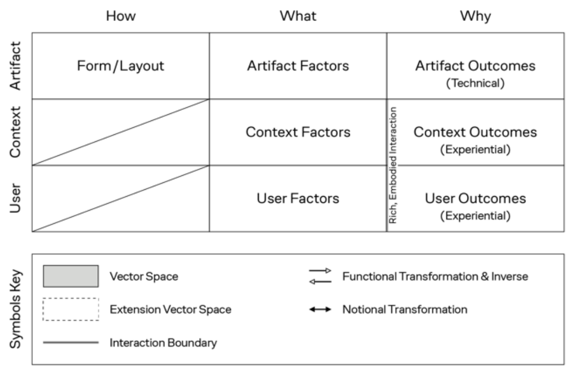

Figure 1. The Actor-Abstraction matrix (top) and associated graphical notation (bottom)

2.1 Actors

On the vertical axis, the Actors dimension describes the three core elements to any product interaction: the *Artifact*, the *User*, and the *Context* of use (Park et al., 2013; Zarour and Alharbi, 2017), i.e., “a user interacts with some subset of features and affordances [of the artifact], based on location in a context, prior experience, and current emotional state” (Forlizzi and Ford, 2000). The Artifact, i.e., the product, is the subject of the design problem. The User is the person who is physically interacting with the product in question. The User both *influences*, and is *influenced by* a product interaction in terms of the experience they have. The Context is the situation for which the interaction takes place. The Context is placed in between the Artifact and the User in Figure 1, as these two Actors meet within the Context. These Actors are then each deconstructed across three levels of *Abstraction.*

2.2 Abstractions

In design, low-level, concrete design decisions are made to achieve high-level, abstract design outcomes. Unfortunately, the designer cannot simply manifest the outcomes that they wish for a product to achieve; they must make decisions according to the *design levers* available to them, and understand how these levers produce desired outcomes. The manner in which these high-level

https://doi.org/10.1017/pds.2023.4 Published online by Cambridge University Press

outcomes are determined by low-level decisions may be conceptualized as a series of transformations between different levels of abstraction (Eisentraut and Günther, 1997). These levels may be defined by the *How*, the *What*, and the *Why* (Hassenzahl, 2018), in which How is the most concrete and Why is the most abstract (Desmet et al., 2008). Each of these levels is elaborated on in turn, and the manner in which they break down across the three Actors is summarized in Table 1.

Table 1. The Actor-Abstraction (A-A) domains

Actor	Abstraction	Description	Examples
Artifact	How	How the *form/layout* of the Artifact is composed.	Geometric dimensions, structure, materials, etc.
	What	What the Artifact is from a consumer perspective. This describes its attributes that *factor* into a defined product interaction.	Strength, weight, haptic feedback, etc.
	Why	Why the product was created in the way it was from a performance standpoint. This describes the *technical outcomes* that are inherent to the artifact itself, regardless of any interaction.	Durability, affordability, etc.
Context	What	What the Context for the interaction is. This describes environmental attributes, which *factor* into the product interaction.	Physical, digital, social environments, etc.
	Why	Why the product was created in the way it was from an experiential standpoint, with regard to some task. This describes the *experiential outcomes* that are external to the User, and may be observed in the context of the interaction.	Efficiency, effectiveness, error rate, etc.
User	What	What the characteristics of the User are. This describes their personal attributes, which *factor* into the product interaction.	Predispositions, demographics, expectations, skills, etc.
	Why	Why the product was created in the way it was from an experiential standpoint, with regard to User's elicited reaction. This describes the *experiential outcomes* that are internal to the user, and may be assessed through subjective perceptions or physiological responses.	Pleasure, satisfaction, heart-rate, arousal, perceptions, etc.

At the lowest, most concrete level is the *How*, i.e., how each actor is formed or composed to exist as they do. In this work, this level is especially pertinent to the Artifact, as it represents how the product is engineered. This level specifies the geometric dimensions of its *form/layout*, which can include its structure, materials, and any other components that may be selected, altered, or interchanged in a measurable manner (Van den Hoven et al., 2007). It is important to note here that the other actors—the User and the Context—are omitted for this abstraction level. This is due the intended audience of this work being a product designer, whose design levers primarily regard how the Artifact is composed. Although the product designer must account for each of these other Actors, they are only relevant at the level of the What and Why. That is not to say that these domains do not exist or that they cannot be defined, however for the purposes of this work, their omission does not hinder any discussion.

Between the How and the Why is the *What*, i.e., what each actor *is* in terms of what it independently brings to the interaction. This level specifies the relevant *factors* of the artifact, user, and context that directly influence the product interaction. For the Artifact, this refers to the 'bundles of attributes' that are traditionally used to describe the artifact from the user's perspective (Michalek et al., 2005). For the User, this refers to the intrinsic characteristics that they may have *before* the product interaction occurs, such as emotions, feelings, values, prior experiences, cognitions (Forlizzi and Ford, 2000), perceptions (Hassenzahl, 2018), motives, abilities, preferences (Desmet and Hekkert, 2007),

https://doi.org/10.1017/pds.2023.4 Published online by Cambridge University Press

expectations, goals, (Hassenzahl and Tractinsky, 2006), psychological or ideological predispositions (Siu, 2005), etc. More objective aspects like human factors/ergonomics (Sun et al., 2019), or demographic qualities (e.g., age, gender, ethnicity, culture, etc.) (Park et al., 2013) can fall under this umbrella as well. For the Context, this refers to the defining aspects of the environment that situate this interaction. This may include aspects of the physical environment (Chung and Fortier, 2013), but also may be considered by the social, economic (Desmet and Hekkert, 2007), or organizational settings (Hassenzahl and Tractinsky, 2006) that influence the interaction. The influence of Context may by illustrated by the anecdote, "a convertible in one's garage is not the same as driving open-topped through lush hills on a beautiful summer evening" (Hassenzahl, 2007).

At the highest, most abstract level is the *Why*, i.e., why this product was created in the way that it was. This level specifies the relevant *outcomes* of the Artifact, Context, and User that the product designer considers. In terms of the Artifact, these outcomes refer to its inherent *technical* outcomes, such as durability or affordability. Alternatively, outcomes can be *experiential* in nature. 'Experience' is typically discussed in terms of user experience (UX) or usability (Rajeshkumar et al., 2013). UX describes the "user's perceptions and responses that result from the use and/or anticipated use of a product, system or service" (ISO, 2019). Usability is "the extent to which a system, product or service can be used by specified users to achieve specified goals with effectiveness, efficiency and satisfaction in a specified context of use" (ISO, 2018). The relationship between the concepts of 'UX' and 'usability' is fuzzy (Law, 2011) and has evolved over time (Zarour and Alharbi, 2017). In the A-A matrix, this line is drawn between those experiential outcomes that are *internal* to the User and those that are *external*, i.e., those that are only measurable through the completion of a task within the context of use. The former are considered *User outcomes*, e.g., subjective perceptions or physiological responses that may be measured directly from the user to assess internal emotional, cognitive, or perceptual states. The latter are considered *Context outcomes*, e.g., efficiency or effectiveness, which are measured in relation to the completion of a task that takes place in an environment.

2.3 Graphical Notation

The 'symbols key' given in Figure 1 provides a symbolic 'grammar' that may be used to map precise design methods within the Actor-Abstraction matrix. The symbols in this graphical notation are first each defined in general terms according to what they represent and how they may be used.

Within each cell (i.e., A-A domain), specific *vector spaces* may be defined as subsets of the relevant considerations within the larger domain. For instance, while the User-Why domain contains all of the perceptions, cognitions, emotions, bodily responses, etc. that may internally result from a product interaction, it may be more practical for the product designer to only consider their User outcomes by some fixed set of perceptions that they may be measured on a sematic differential scale. These ratings would therefore span a discreet vector space defined within the User-Why. Other A-A domains may not be especially relevant or necessary to consider at all in some design problems, such that *no* vector spaces are defined for the specific design method. Vector space *extensions* refer to new vector spaces that may be added on to an existing formulation. This could be from practitioners adding on to existing design methods, or from new iterations of a design problem that bring new considerations.

The relations between vector spaces are given by *transformations*, which are represented here by different types of connective arrows that may be drawn between the vector space boxes. The type of arrow indicates the manner in which this transformation is characterized. Functional transformations are characterized through mathematical models, and are given by white, unidirectional arrows; these models can have an inverse that may describe the transformation in the opposite direction. Alternatively, domains that are related, but not necessarily with the level of specificity provided by a mathematical model, are coupled through *notional transformations*. These are given by bi-directional, black arrows. An example of a notional transformations would be the symbolic relations often used in Quality Function Deployment (e.g., symbols to denote strong/weak relations).

The *interaction boundary* defines a specific boundary between domains in the A-A matrix. Located between the Context/User-What and the Context/User-Why, this boundary denotes the area in which it is necessary for a product interaction to occur for the What to be transformed into the Why. This essentially serves to differentiate the Artifact outcomes—which exist regardless of any interaction—from the Context and User outcomes—which do not. From a modeling perspective, any transformation that crosses this distinguished boundary must be characterized empirically. Other transformations that do not cross this boundary may be instead characterized analytically (e.g., through FMEA, etc.).

https://doi.org/10.1017/pds.2023.4 Published online by Cambridge University Press

3 MAPPING DESIGN METHODS IN THE ACTOR-ABSTRACTION MATRIX

The Actor-Abstraction matrix was defined as a boundary object so that it could be flexibly compatible with multiple design methods and perspectives. The best test of this claimed flexibility is to map each of the four design methods into the matrix, and construct multiple different precise formulations within this common framework. By translating these disparate methods into a common ontology, certain commonalities (and therefore, distinctions) may be identified (Tharchen et al., 2020). The results of this mapping are illustrated in Figure 2.

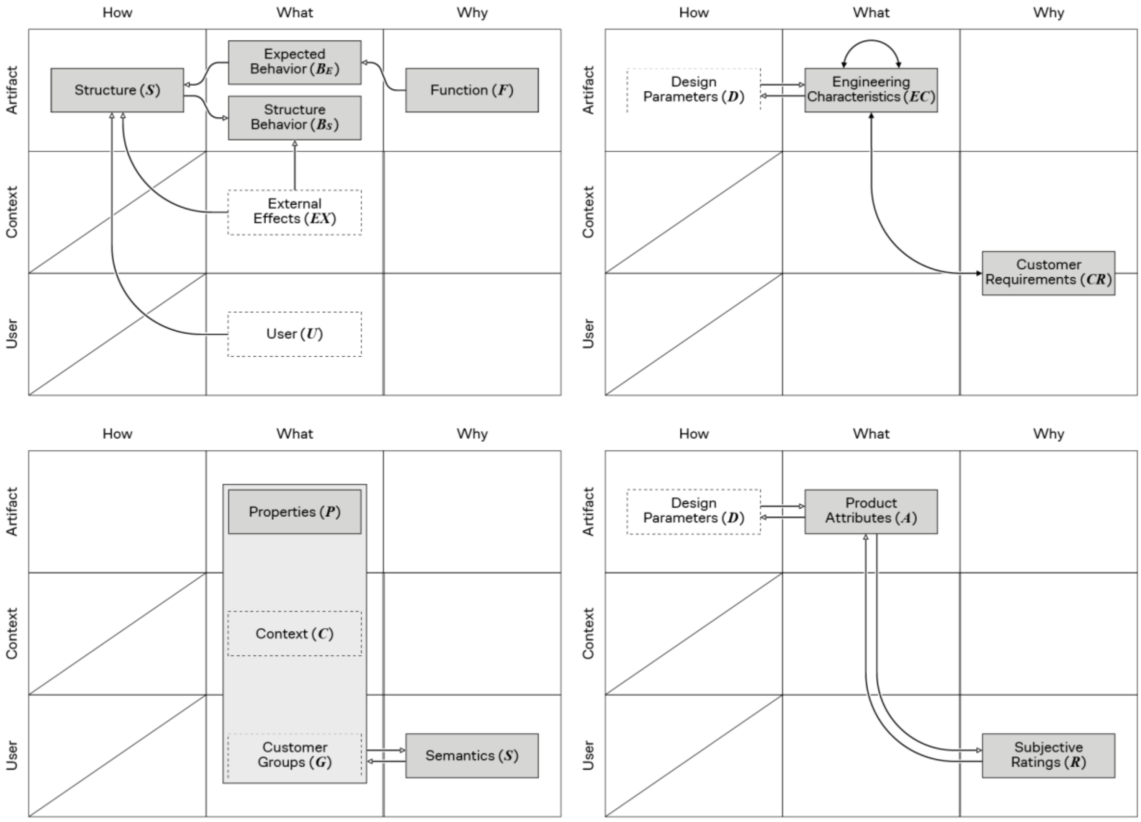

Figure 2. FBS (top left), QFD (top right), KE (bottom left), and CA (bottom right) mapped into the Actor-Abstraction (A-A) matrix

This mapping exercise therefore serves two purposes, which are to: 1) demonstrate the A-A matrix's effectiveness as a boundary object by flexibly supporting each of these independently developed design methods, and to 2) place each of these design methods onto a uniform scale for which they may be contrasted against not only each other, but also any other methods that may be mapped on this same scale. This exercise relies on a certain degree of interpretation to conduct the necessary meta-analysis of different works that have applied each method. Every practitioner who uses these existing design methods may have modified or reinterpreted them to better suit their individual needs. Nevertheless, the commonality between all these design methods is that they simply describe a transformation, which is packaged inside their unique conceptual 'wrappers' (i.e., their terminologies, experimental procedures, visualization tools, etc.). While the transformation has an intended input and output domain, the model that is often used to characterize such a transformation may be capable of more broadly supporting different inputs/outputs than the individual method may intend; the model itself is not aware of the types of data that comprise its inputs/outputs. This interpretive meta-analysis therefore attempts to map the *intended* usage of these methods, rather than capturing all formulations that may be mathematically possible.

3.1 Mapping Function-Behaviour-Structure

The Function-Behavior-Structure framework may be mapped to the A-A matrix (see Figure 1, top left) by classifying the Function (*F*), Behavior (*B*), and Structure (*S*) vector spaces into A-A domains. At

https://doi.org/10.1017/pds.2023.4 Published online by Cambridge University Press

the level of the Why, *F* defines why the product was created. Practitioners have stated that 'experience' is taxonomically distinct from 'function' in the manner that it is typically described (Murakami and Koyanagi, 2017), and consideration of experiential responses in FBS is relatively rare (Sadeghi et al., 2017). *F* may therefore be mapped into the Artifact-Why domain, as it principally regards the technical Artifact outcomes. At the level of the What, *B* describes what the Artifact does, and may, of course, be mapped into the Artifact-What. However, in *situated* FBS, *B* is decomposed into two sub-vector spaces—the Structure Behavior (B_S) that is coupled to *S* with a functional transformation, and the Expected Behavior (B_E) that is coupled to *F* and *S* with functional transformations. Finally, at the level of the How, *S* describes how the Artifact is composed, and may be mapped into the Artifact-How. There also exists several extensions to this framework. One extension, for instance, added 'exogeneous variables' such as temperature to this formulation (Qian and Gero, 1996); an External Effects (*EX*) extension vector space may therefore be mapped into the Context-What, which is coupled to S with functional transformations. Another extension added 'user' factors such as 'profession, experience, expertise, gender, age, etc.' into the formulation (Houssin et al., 2010); a User (*U*) extension vector space may therefore be also mapped into the User-What, and coupled to *S* with a functional transformation.

3.2 Mapping Quality Function Deployment

Quality-Function-Deployment may be mapped to the A-A matrix (see Figure 1, top right) by classifying the Customer Requirements (*CR*) and Engineering Characteristics (*EC*) vector spaces into A-A domains. At the level of the Why, *CR*, otherwise commonly known as the 'voice of the customer' (Kiran, 2016), defines why the product was created. This vector space could fall into the User-Why, as users are able to provide their subjective rating, or potentially in the Context-Why, as users typically interact with real versions of the product and can complete tasks with them; it is mapped between both A-A domains in this formulation. *CR* would not cover the Artifact-Why (Sener and Karsak, 2011), however, as customers typically have difficulty voicing technical requirements (Cross, 2021) and an traditional engineering approach would be more appropriate for propagating outcomes on this level. At the level of the what, *EC* describes attributes of the Artifact that are relevant to the User, and may therefore be mapped into the Artifact-What. *CR* is coupled to *EC* with only a notional transformation in the body House of Quality (HOQ) matrix; *EC* is also coupled back to itself with another notional transformation in the head of this matrix. While the name 'Engineering Characteristics' may sound better suited to the Artifact-How, it is evidenced by the later addition of a Design Parameters (*D*) extension vector space that is explicitly in this A-A domain (Ramaswamy and Ulrich, 1993) (alternatively, see 'part characteristics' (Kiran, 2016)), that *EC* is correctly attributed to the level of the What. *D* is then coupled to *EC* with functional transformations.

3.3 Mapping Kansei Engineering

Kansei Engineering may be mapped to the A-A matrix (see Figure 1, bottom left) by classifying the Semantics (*S*) and Properties (*P*) vector spaces into A-A domains. At the level of the Why, *S*, defines the Kansei words (i.e., emotions) that the product was created to achieve. These emotional responses are internal to the User, so *S* may be mapped into the User-Why. At the level of the What, *P* describes observable, influential attributes of the artifact, and may therefore be mapped into the Artifact-What. *S* is coupled to *P* with a functional transformation that is typically characterized by a statistical model. Practitioners have added in a Customer Groups (*G*) extension vector space (Schütte, 2002) and a Context (*C*) extension vector space (Wellings et al., 2010) into this functional transformation. These map into the User-What and Context-What domains, respectively.

3.4 Mapping Conjoint Analysis

Conjoint Analysis may be mapped to the A-A matrix (see Figure 1, bottom right) by classifying the Product Attributes (*A*) and Subjective Ratings (*R*) vector spaces into A-A domains. At the level of the Why, *R* defines the scores that users may subjectively rate the product, which may be mapped into the User-Why. If the conjoint survey is administered through a *choice-based* format, this method would not map as cleanly onto the A-A matrix, as judgements such as 'choice' or 'purchase decision' are a higher level of abstraction that are made based on an aggregation of technical and experiential outcomes (Boatwright and Cagan, 2010; Kang et al., 2018; Tovares et al., 2014). This would require

https://doi.org/10.1017/pds.2023.4 Published online by Cambridge University Press

adding a fourth level of abstraction (i.e., a *'So-What'* column) to the matrix to support this format. At the level of the What, *A* describes the attributes of the product that are most relevant to the consumer, and is therefore mapped into the Artifact-What. *R* is coupled to *A* with a functional transformation that is characterized by a statistical model. At the level of the How, engineers have added in a Design Parameters (*D*) extension vector space that describes the underlying form/layout of the artifact (Michalek et al., 2005); this is mapped into the Artifact-How. *D* is then coupled to *A* with a functional transformation that is characterized by an analytical engineering model.

4 DISCUSSION

Overall, this mapping of existing design methods puts the flexibility of the Actor-Abstraction matrix to the test across a variety of different perspectives and disciplines. While there are some select instances in which vector spaces fall outside the defined scope of the A-A matrix (e.g., choice-based Conjoint Analysis formats that address higher abstractions), the boundary object can demonstrably support each of these design methods. While the interpretations to construct these maps may arguably be imperfect, they nevertheless enable comparisons that were previously more difficult or impossible to make.

Mapping each of these design methods onto this common scale can suggest areas in which they may be integrated with each other, a proposition that was previously ambiguous. In terms of boundary objects, a 'boundary' is often misconstrued as a line that differentiates design methods, but in reality is an area in which they overlap (Star, 2010). This mapping highlights these overlaps, which signal areas in which boundaries may be spanned, i.e., points of compatibility for general usage. For instance, the Design Parameters (*D*) extension vector space defined in both Quality Function Deployment (Ramaswamy and Ulrich, 1993) and Conjoint Analysis (Michalek et al., 2005) couples the Artifact-How to the Artifact-What. As Kansei Engineering defines a Properties (*P*) vector space in the Artifact-What—thus overlapping this transformation—it stands to reason that these extensions may also be compatible with KE. Of course, any claims of compatibility for the existing design methods that are suggested by these mappings must be independently validated in future works. By including extensions in this mapping exercise, a picture emerges of why these works were motivated—to fill gaps in these formulations. Other A-A domains that are not addressed in these mappings may therefore suggest *additional* areas in which these works could serve to be extended. Mapping these extensions also illustrates how continued methodological development can be supported by this tool. As such, another key benefit of this exercise is to identify gaps for *new* design methods. Rather than meticulously testing these identified points of compatibility and knitting all of these existing methods together, it may be more prudent to selectively integrate only what is needed into the creation of new design methods. In doing so, designers may take advantage of the benefits of each method, without being burdened by their associated limitations that may be included in their wholesale adoption.

5 CONCLUSION

Existing design methods are well understood in their own right, but less so in relation to alternative methods from different disciplines or perspectives. In this work, a boundary object for design methods is developed in the form of the Actor-Abstraction matrix. With this tool, the designer's vocabulary and conceptualization of the design problem may be flexibly formulated to support a variety of different disciplines and perspectives. At first, the A-A matrix imparts a looser organizational structure, which is important for enabling multidisciplinary support. This is evidenced by the more precise organizational structures that may be mapped into this matrix to allow for visual comparison of the different design methods. This paints a clearer picture of where the boundaries between these methods exist, and how they may be extended or integrated together. With such a tool, designers may not only retroactively map existing design methods so they may better understand their application in relation to available alternatives, but could also provide an important platform to support *new* methodological development in future works. These new methods could address gaps in existing methods that highlighted by their mapping in this matrix. As the development of new design methods is the foundational aim of design science, this could serve as a valuable tool for advancing this field.

https://doi.org/10.1017/pds.2023.4 Published online by Cambridge University Press

REFERENCES

Al-Fedaghi, S. (2016), "Function-Behavior-Structure Model of Design: An Alternative Approach", *International Journal of Advanced Computer Science and Applications*, Vol. 7, https://dx.doi.org/10.14569/IJACSA.2016.070719.

Blessing, L.T. and Chakrabarti, A. (2009), *DRM: A Design Reseach Methodology*, Springer.

Boatwright, P. and Cagan, J. (2010), *Built to Love: Creating Products That Captivate Customers*, Berrett-Koehler Publishers.

Chung, W. and Fortier, S. (2013), "Context as a System, Product as a Component, and the Relationship as Experience", in Marcus, A. (Ed.), *Design, User Experience, and Usability. Design Philosophy, Methods, and Tools*, Springer, Berlin, Heidelberg, pp. 29–37, https://dx.doi.org/10.1007/978-3-642-39229-0_4.

Cross, N. (2021), *Engineering Design Methods: Strategies for Product Design*, John Wiley & Sons.

Desmet, P. and Hekkert, P. (2007), "Framework of Product Experience", p. 11.

Desmet, P.M.A., Ortíz Nicolás, J.C. and Schoormans, J.P. (2008), "Product personality in physical interaction", *Design Studies*, Vol. 29 No. 5, pp. 458–477, https://dx.doi.org/10.1016/j.destud.2008.06.003.

Eisentraut, R. and Günther, J. (1997), "Individual styles of problem solving and their relation to representations in the design process", *Design Studies*, Vol. 18 No. 4, pp. 369–383, https://dx.doi.org/10.1016/S0142-694X(97)00007-0.

Forlizzi, J. and Ford, S. (2000), "The building blocks of experience: an early framework for interaction designers", *Proceedings of the 3rd Conference on Designing Interactive Systems: Processes, Practices, Methods, and Techniques*, Association for Computing Machinery, New York, NY, USA, pp. 419–423, https://dx.doi.org/10.1145/347642.347800.

Gero, J.S. (1990), "Design Prototypes: A Knowledge Representation Schema for Design", *AI Magazine*, Vol. 11 No. 4, pp. 26–26, https://dx.doi.org/10.1609/aimag.v11i4.854.

Gero, J.S. and Kannengiesser, U. (2014), "The function-behaviour-structure ontology of design", *An Anthology of Theories and Models of Design*, Springer, pp. 263–283.

Gerrike, K., Eckert, C. and Stacey, M. (2017), "What do we need to say about a design method?", presented at the 21th International Conference on Engineering Design (ICED 2015), Vancouver, Canada.

Green, P.E. and Srinivasan, V. (1990), "Conjoint Analysis in Marketing: New Developments with Implications for Research and Practice", *Journal of Marketing*, SAGE Publications Inc, Vol. 54 No. 4, pp. 3–19, https://dx.doi.org/10.1177/002224299005400402.

Gregory, S.A. (2014), *The Design Method*, Springer US.

Hassenzahl, M. (2007), "The hedonic/pragmatic model of user experience", *Towards a UX Manifesto*, pp. 10–14.

Hassenzahl, M. (2018), "The Thing and I (Summer of '17 Remix)", in Blythe, M. and Monk, A. (Eds.), *Funology 2: From Usability to Enjoyment*, Springer International Publishing, Cham, pp. 17–31, https://dx.doi.org/10.1007/978-3-319-68213-6_2.

Hassenzahl, M. and Tractinsky, N. (2006), "User experience - a research agenda", *Behaviour & Information Technology*, Taylor & Francis, Vol. 25 No. 2, pp. 91–97, https://dx.doi.org/10.1080/01449290500330331.

Houssin, R., Sun, H. and Gardoni, M. (2010), "A behavioural design approach to improving mechanical system design with integration of use conditions", *International Journal of Design and Innovation Research*, Vol. 5 No. 3, pp. 1–24.

ISO. (2018), *Ergonomics of Human-System Interaction—Part 11: Usability: Definitions and Concepts*, No. ISO 9241-11:2018, International Standardization Organization (ISO), Switzerland.

ISO. (2019), "ISO 9241-210:2019", ISO.

Kang, X., Yang, M., Wu, Y. and Ni, B. (2018), "Integrating Evaluation Grid Method and Fuzzy Quality Function Deployment to New Product Development", *Mathematical Problems in Engineering*, Hindawi, Vol. 2018, p. e2451470, https://dx.doi.org/10.1155/2018/2451470.

Kiran, D.R. (2016), *Total Quality Management: Key Concepts and Case Studies*, Butterworth-Heinemann.

Law, E.L.-C. (2011), "The measurability and predictability of user experience", *Proceedings of the 3rd ACM SIGCHI Symposium on Engineering Interactive Computing Systems*, Association for Computing Machinery, New York, NY, USA, pp. 1–10, https://dx.doi.org/10.1145/1996461.1996485.

Michalek, J.J., Feinberg, F.M. and Papalambros, P.Y. (2005), "Linking Marketing and Engineering Product Design Decisions via Analytical Target Cascading*", *Journal of Product Innovation Management*, Vol. 22 No. 1, pp. 42–62, https://doi.org/10.1111/j.0737-6782.2005.00102.x.

Murakami, T. and Koyanagi, T. (2017), "Proposal of Delta Design Map Based on Function, Behavior, Structure and User Experience for Design Ideation Support", presented at the ASME 2017 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference, American Society of Mechanical Engineers Digital Collection, https://dx.doi.org/10.1115/DETC2017-68058.

Nagamachi, M. (2016), *Kansei/Affective Engineering*, CRC Press.

Neto, W.F. and Pires, A.R. (2020), "Kansei Engineering and Quality Function Deployment: Development of Methodology for the Identification of User-Centralized Project Improvements", in Fukuda, S. (Ed.),

Advances in Affective and Pleasurable Design, Springer International Publishing, Cham, pp. 300–309, https://dx.doi.org/10.1007/978-3-030-20441-9_32.
Papalambros, P.Y. (2015), "Design Science: Why, What and How", *Design Science*, Cambridge University Press, Vol. 1, https://dx.doi.org/10.1017/dsj.2015.1.
Park, J., Han, S.H., Kim, H.K., Oh, S. and Moon, H. (2013), "Modeling user experience: A case study on a mobile device", *International Journal of Industrial Ergonomics*, Vol. 43 No. 2, pp. 187–196, https://dx.doi.org/10.1016/j.ergon.2013.01.005.
Qian, L. and Gero, J.S. (1996), "Function–behavior–structure paths and their role in analogy-based design", *AI EDAM*, Cambridge University Press, Vol. 10 No. 4, pp. 289–312.
Rajeshkumar, S., Omar, R. and Mahmud, M. (2013), "Taxonomies of User Experience (UX) evaluation methods", 2013 *International Conference on Research and Innovation in Information Systems (ICRIIS)*, presented at the 2013 International Conference on Research and Innovation in Information Systems (ICRIIS), pp. 533–538, https://dx.doi.org/10.1109/ICRIIS.2013.6716765.
Ramaswamy, R. and Ulrich, K. (1993), "Augmenting the house of quality with engineering models", *Research in Engineering Design*, Vol. 5 No. 2, pp. 70–79, https://dx.doi.org/10.1007/BF02032576.
Sadeghi, L., Dantan, J.-Y., Mathieu, L., Siadat, A. and Aghelinejad, M.M. (2017), "A design approach for safety based on Product-Service Systems and Function–Behavior–Structure", *CIRP Journal of Manufacturing Science and Technology*, Vol. 19, pp. 44–56, https://dx.doi.org/10.1016/j.cirpj.2017.05.001.
Schütte, S. (2002), "Designing Feelings into Products : Integrating Kansei Engineering Methodology in Product Development", Institutionen för konstruktions- och produktionsteknik.
Sener, Z. and Karsak, E.E. (2011), "A combined fuzzy linear regression and fuzzy multiple objective programming approach for setting target levels in quality function deployment", *Expert Systems with Applications*, Vol. 38 No. 4, pp. 3015–3022, https://dx.doi.org/10.1016/j.eswa.2010.08.091.
Singh, R.K., Rajput, V. and Sahay, A. (2018), "A Literature Review On Quality Function Deployment (QFD)", *IAETSD Journal For Advanced Research In Applied Sciences*, Vol. 5 No. 8, pp. 245–250.
Siu, K.W.M. (2005), "Pleasurable products: public space furniture with userfitness", *Journal of Engineering Design*, Taylor & Francis, Vol. 16 No. 6, pp. 545–555, https://dx.doi.org/10.1080/09544820500273383.
Star, S.L. (2010), "This is Not a Boundary Object: Reflections on the Origin of a Concept", *Science, Technology, & Human Values*, SAGE Publications Inc, Vol. 35 No. 5, pp. 601–617, https://dx.doi.org/10.1177/0162243910377624.
Star, S.L. and Griesemer, J.R. (1989), "Institutional Ecology, 'Translations' and Boundary Objects: Amateurs and Professionals in Berkeley's Museum of Vertebrate Zoology, 1907-39", *Social Studies of Science*, SAGE Publications Ltd, Vol. 19 No. 3, pp. 387–420, https://dx.doi.org/10.1177/030631289019003001.
Sun, X., Houssin, R., Renaud, J. and Gardoni, M. (2019), "A review of methodologies for integrating human factors and ergonomics in engineering design", *International Journal of Production Research*, Vol. 57 No. 15–16, pp. 4961–4976, https://dx.doi.org/10.1080/00207543.2018.1492161.
Tharchen, T., Garud, R. and Henn, R.L. (2020), "Design as an interactive boundary object", *Journal of Organization Design*, Vol. 9 No. 1, p. 21, https://dx.doi.org/10.1186/s41469-020-00085-w.
Tovares, N., Boatwright, P. and Cagan, J. (2014), "Experiential Conjoint Analysis: An Experience-Based Method for Eliciting, Capturing, and Modeling Consumer Preference", *Journal of Mechanical Design*, Vol. 136 No. 101404, https://dx.doi.org/10.1115/1.4027985.
Van den Hoven, E., Frens, J., Aliakseyeu, D., Martens, J.-B., Overbeeke, K. and Peters, P. (2007), "Design research & tangible interaction", *Proceedings of the 1st International Conference on Tangible and Embedded Interaction*, Association for Computing Machinery, New York, NY, USA, pp. 109–115, https://dx.doi.org/10.1145/1226969.1226993.
Wang, C.-H. (2015), "Integrating Kansei engineering with conjoint analysis to fulfil market segmentation and product customisation for digital cameras", *International Journal of Production Research*, Taylor & Francis, Vol. 53 No. 8, pp. 2427–2438, https://dx.doi.org/10.1080/00207543.2014.974840.
Wellings, T., Williams, M. and Tennant, C. (2010), "Understanding customers' holistic perception of switches in automotive human–machine interfaces", *Applied Ergonomics*, Vol. 41 No. 1, pp. 8–17, https://dx.doi.org/10.1016/j.apergo.2009.03.004.
Yannou, B., Cluzel, F. and Lamé, G. (2018), "Adapting the FBS Model of Designing for Usage-Driven Innovation Processes", presented at the ASME 2018 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference, American Society of Mechanical Engineers Digital Collection, https://dx.doi.org/10.1115/DETC2018-86166.
Zarour, M. and Alharbi, M. (2017), "User experience framework that combines aspects, dimensions, and measurement methods", edited by Park, E.*Cogent Engineering*, Vol. 4 No. 1, p. 1421006, https://dx.doi.org/10.1080/23311916.2017.1421006.