DESIGN THINKING, FAST AND SLOW

A Framework for Kahneman's Dual-System Theory in Design

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Abstract. In his book *Thinking, Fast and Slow* Daniel Kahneman presented a model of human cognition based on two modes or "systems" of thinking: system 1 thinking that is fast and intuitive, and system 2 thinking that is slow and tedious. This paper proposes a framework for applying Kahneman's model to designing, based on the function-behaviour-structure (FBS) ontology. It casts four instances of designing in this framework: design fixation, case-based design, pattern language-based design, and brainstorming.

1. Introduction

In recent years design researchers have increasingly attempted to establish links between the design domain and the broader area of cognitive science. This aims to foster the development of common models and theories across the two domains, and to remove some of the inconsistencies within design research by relating them to more established notions and terms in cognitive science (Hay et al. 2017). Methods and advances in cognitive science can then flow into design science. This can also provide design practitioners access to a new range of methods and tools such as creativity tools (Howard et al. 2008).

One well-established model of human thinking from cognitive psychology that is supported by numerous empirical studies is the dual-system theory, or sometimes called dual-process theory (Wason and Evans 1975; Sloman 1996; Stanovich and West 2000; Kahneman and Frederick 2002; Evans and Stanovich 2013). A number of accounts of this theory exist that differ in a few details (Evans and Stanovich 2013). Daniel Kahneman, in his book *Thinking, Fast and Slow* (Kahneman 2011), made dual-system theory accessible to people outside cognitive psychology. What is common to all accounts of dual-system theory is that human cognition is described to be governed by two systems: system 1 for fast, intuitive and effortless thinking, and system 2 for slower, analytic thinking that requires greater cognitive effort. System 1 is assumed to govern much of our daily behaviour. It is only when the fast responses generated by system 1 do not produce the results expected that

system 2 comes into play. Dual-system theory challenges common beliefs of ourselves as rational beings that process information and take decisions objectively and analytically.

In this paper we examine the link between dual-system theory and a special area of human cognition: design thinking. Design thinking has a tradition as a scientific study (e.g. Simon (1969)). Recently, it has been understood as a notion covering a set of techniques for stimulating creative solutions to problems in business, education and social domains (Brown 2009, Verganti 2009, Liedtka and Ogilvie 2011). This paper uses the concept of design thinking in the more general sense, encompassing the specific techniques applied in different domains. It thereby aims to lay the foundations for improved design tools: If dual-system theory plays a role in design, then tool support for system 1 and system 2 design thinking is likely to differ. The work presented here contributes to the development of such design support by identifying the locations of the two modes of design thinking.

Specifically, we relate dual-system theory and design thinking based on the function-behaviour-structure (FBS) ontology (Gero 1990; Gero and Kannengiesser 2004; Gero and Kannengiesser 2014). System 1 design thinking is shown as a new process within the FBS ontology. The FBS ontology is viewed as a suitable framework for the purposes of this study because it is widely referenced in academia (currently more than 3,000 citations on Google Scholar for the two papers: Gero (1990) and Gero and Kannengiesser (2004)) and its meta-cognitive, descriptive perspective that focuses on individual mental activities of designing (Wynn and Clarkson 2018). The "micro-level" (*ibid.*) focus of the FBS ontology has enabled its widespread use as a coding schema for design protocols. Studies carried out include aerospace system development projects in industry, where more than 10,000 hours of designing spread over multiple years were coded based on FBS (Bott and Mesmer 2019). Using the FBS ontology as a basis for representing dual-system theory can therefore provide the foundation for empirically testing the hypothesis that system 1 and system 2 thinking occur in design.

The paper is organised as follows: Section 2 describes the foundations of dual-system theory mainly based on Kahneman's (2011) account. Section 3 presents previous research on design thinking and its relation to fast and slow modes of reasoning. Section 4 introduces the FBS ontological model of design thinking. Section 5 represents the two systems in the FBS ontology and explains how they interact. Section 6 casts instances of fast and slow design thinking in this ontology. These cover design fixation, case-based design, pattern-language based design and brainstorming. Section 7 discusses these examples. Section 8 concludes the paper with a summary and discussion of future work.

2. Dual-System Theory

According to dual-system theory, human cognition has two distinct types of thinking: one that is fast, automatic and effortless, and one that is slow, analytic and effortful. This theory originates from the 1970s (e.g. Wason and Evans 1975) and is now well established with a large amount of experimental evidence in cognitive psychology and neuroscience. While the two types of thinking are independent of particular areas in the brain (Evans and Stanovich 2013), Kahneman (2011) refers to them as "system 1" and "system 2", respectively. He does this to enable his readers to conceptualise them as two different characters with distinct personalities rather than as abstract concepts, and thus to facilitate understanding. In this paper, we will also use Kahneman's terms and descriptions. This is to build on Kahneman's successful transfer of dual-system theory concepts outside the cognitive science domain, thus enabling their understanding by design scientists.

Most of Kahneman's (2011) book is about system 1. This is because its influence on human reasoning is underestimated by many people, who are commonly convinced about the rationality and objectiveness of their beliefs, decisions and actions. Kahneman shows that system 1 is involved in a large part of human reasoning, which becomes most evident by the many systematic errors of judgement (also called cognitive biases). One of the examples provided by Kahneman (2011, p. 44) is based on the so-called "bat-and-ball problem":

> "A bat and ball cost $1.10.
> The bat costs one dollar more than the ball.
> How much does the ball cost?"

While the correct answer to this problem is 5¢, most people's intuition tells them it is 10¢. The fast but wrong response generated by system 1 in this case was not challenged by system 2. The reason is on the one hand that system 1 is "overconfident" (*ibid.*). On the other hand, system 2 is "lazy" (*ibid.*): It directs attention for system 1 and then relies on its automatic response, rather than spending effort in checking the correctness of that response. Errors are detected only when they are obvious or when a likely risk of failure is known in advance.

Despite the various fallacies of fast thinking, system 1 also provides a tool for responding to uncertain or ambiguous situations where the use of analytical reasoning would be impossible or impractical. This is done by what Kahneman calls "substitution" (*ibid.*): replacing complex problems by simpler ones. For example, the question "How happy are you with your life these days?", which may be rather difficult to answer analytically, can be substituted by the simpler question "What is my mood right now?", which can be answered quite quickly by system 1 (Kahneman 2011, p. 98). Substitution thus provides us with imperfect yet often adequate answers to difficult questions.

The use of system 1 in these situations is not completely under our control. Kahneman illustrates this with a well-known optical illusion of the kind depicted in Figure 1. As printed on the page, the three human figures are of equal size. Yet, the figure on the left appears larger than the one on the right. This is because the cues contained in the image suggest a 3D interpretation, making system 1 automatically substitute the question posed in the caption of Figure 1 with the following: "How tall are the three people?" (Kahneman 2011, p. 101).

The three-people example shows that another characteristic of system 1 is that it performs many computations at once, many of which are contextual and beyond our conscious control. Kahneman (2011, p. 95) calls this the "mental shotgun":

> "[…] we often compute much more than we want or need. I call this excess computation the *mental shotgun*. It is impossible to aim at a single point with a shotgun because it shoots pellets that scatter, and it seems almost equally difficult for System 1 not to do more than System 2 charges it to do."

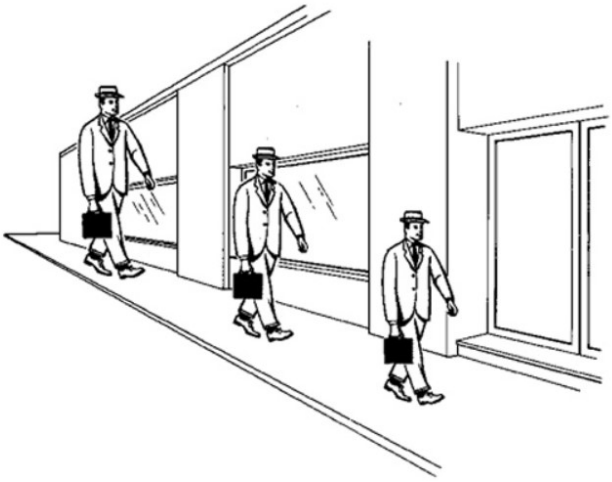


Figure 1. Are the three figures, as printed on the page, of different size? (Source: https://therealweeklyshow.wordpress.com/2014/01/15/5-more-mind-bending-optical-illusions/)

A summary of characteristics commonly ascribed to system 1 and system 2, respectively, is provided in Table 1. It is based on a list of attributes compiled by Evans and Stanovich (2003).

TABLE 1. Characteristics of system 1 and system 2

System 1	System 2
Does not require working memory	Requires working memory
Autonomous	Cognitive decoupling; mental simulation
Fast	Slow
High capacity	Capacity limited
Parallel	Serial
Nonconscious	Conscious
Biased responses	Normative responses
Contextualised	Abstract
Automatic	Controlled
Associative	Rule-based
Experience-based decision making	Consequential decision making
Independent of cognitive ability	Correlated with cognitive ability

3. Does a Fast Mode of Design Thinking Exist?

Designing is commonly viewed as a complex activity that is not associated with a fast, effortless mode of thinking. Most design processes in industry take place within timeframes of weeks and months, and in some cases several years. Even the accomplishment of design exercises in university classrooms takes at least a couple of hours – which is very slow compared to most instances of fast, intuitive thinking provided by system 1. Yet, a number of theoretical and empirical studies show that a fast mode of thinking does play a role in design, at least for parts of the design process.

Fostering fast design thinking has been one of the goals of research in design methods. For example, design catalogues (Roth 2000), selection charts (Pahl and Beitz 2007) and design patterns (Alexander et al. 1977; Gamma et al. 1995) can be viewed as methods for increasing the efficiency with which designers come up with design concepts and solutions. They are based on collections of existing design solutions that are indexed and stored for fast reuse by designers when confronted with similar design problems. While finding and selecting suitable instances of these methods can be quite time-consuming especially in non-routine design situations, the ultimate goal is always to speed up the process of design synthesis based on codifications of previous design knowledge.

Recent studies examine the role of intuition or gut feeling in design. Badke-Schaub and Eris (2014) characterise design intuition as holistic, fast, multisensorial and experience-based. In addition, they see intuition as related to unconscious processes, emotions and creativity. They propose a framework

of design thinking that integrates intuitive and rational decision making. Taura and Nagai (2017) examine the role of intuition in creative design, distinguishing two kinds of intuition: experiential and associative intuition. Experiential intuition uses previously grounded patterns of experience, and associative intuition combines sets of different experiences. The notion of grounding refers to the construction of design experiences based on the interaction of designers with their current view of the world that is formed by their previous experiences and interactions (Gero 1999).

Research in design computing has come up with three modes of reasoning (Maher and Gero 2002) – reflexive, reactive and reflective reasoning – in a design agent these imply different speeds with which they are carried out.

Reflexive reasoning is a direct response of the design agent to specific sets of stimuli. Reasoning here does not entail any internal processing or decision making; it is merely a mapping of sensory input to actions performed by the design agent's effectors. Hence, reflexive reasoning can be considered as fast. Examples include hard-wired, biological reflexes, and habituated responses to recurring stimuli.

Reactive reasoning involves a limited form of interaction between various of the design agent's internal representations. This interaction can be viewed as the process of selecting among several alternatives the most appropriate schema given the stimuli presented, where each alternative is a mapping of sensory input to actions. As a result, agents assess their decisions by monitoring the effects of their actions and comparing them against a set of criteria. Reactive reasoning can still be considered rather fast but requiring slightly more time and effort than reflexive reasoning.

Reflective reasoning involves a more significant amount of interaction between a model of the external world and the design agent's goals and concepts. It is a construction process that uses filtering, emphasising and distorting of certain aspects of the external cues, driven by changes in the agent's expectations. The outcomes of actions devised by this mode of reasoning produce new expectations that provide new criteria for assessing these actions. Reflective reasoning is usually slow and requires high amounts of cognitive effort by the agent.

The three modes of reasoning have been used for a model of affordances (Kannengiesser and Gero 2012; Gero and Kannengiesser 2012) that shares similarities with some of the examples of fast and slow thinking presented in Kahneman's (2011) book. The effect of learning on the three modes of reasoning has been shown computationally by Gero and Peng (2009): When experiences become more grounded in an agent's memory, the corresponding reasoning processes over time transform from being reflective to reactive and then reflexive.

Some evidence for the existence of fast ways of thinking in design comes from empirical studies. Designers are frequently observed to "jump" to concrete design concepts right from the beginning of a design task (Ullman et al. 1988, Lawson 1994, Cross 2001; Kannengiesser and Gero 2017). This may lead to designers getting stuck or ignoring alternative concepts – a phenomenon commonly known as design fixation (Jansson and Smith 1991). It can be seen as a downside of approaches for increasing design efficiency based on previous design solutions.

The designers' preference for swift solutions rather than lengthy analyses has also been observed in other empirical studies even though they have different research goals. For example, the low acceptance of functional modelling methods by design practitioners has partially been explained by their tendency "to avoid abstract and solution-neutral thinking, […] instead preferring to work in a goal/solution-oriented fashion that swiftly leads towards a concrete result" (Eisenbart and Kleinsmann 2017). Similar observations were made by Eckert (2013) and Eisenbart et al. (2017).

4. A Framework for Design Thinking

A framework for design thinking is based on the function-behaviour-structure (FBS) ontology (Gero 1990; Gero and Kannengiesser 2014). It has been proposed as a design ontology that describes all designed things, or artefacts, irrespective of the specific discipline of designing. Its three fundamental constructs – function (F), behaviour (B) and structure (S) – are defined as follows:

Function is the teleology of the artefact ("what the artefact is for"). It is ascribed to the artefact by establishing a connection between one's goals and the artefact's measurable effects.

Behaviour is defined as the artefact's attributes that can be derived from its structure ("what the artefact does"). Behaviour provides measurable performance criteria for comparing different artefacts.

Structure is defined as its components and their relationships ("what the artefact consists of").

Humans construct connections between function, behaviour and structure through experience and through the development of causal models based on interactions with the artefact. Specifically, function is ascribed to behaviour by establishing a teleological connection between the human's goals and the observable or measurable performance of the artefact. Behaviour is causally connected to structure, i.e. it can be derived from structure using physical or other causal-type laws or heuristics. There is no direct connection between function and structure.

The FBS ontology defines the processes of designing and design thinking as transformations between function, behaviour and structure (Gero 1990;

Gero and Kannengiesser 2014). The most basic view of designing consists of transformations from function to behaviour, and from behaviour to structure:

(1) F → B, and

(2) B → S

In this view, behaviour is interpreted as the performance expected to achieve desired function. Yet, once a structure is produced, it must be checked whether the artefact's "actual" performance, based on the structure produced and the operating environment, matches the "expected" behaviour. Therefore, the FBS ontology distinguishes two classes of behaviour: expected behaviour (Be) and behaviour derived from structure (Bs). This extends the set of transformations with which we can describe designing to include:

(1) F → Be,

(2) Be → S,

(3) S → Bs, and

(4) Be ↔ Bs (comparison of the two types of behaviour).

The observable input and output of any design activity is a set of requirements (R) that come from outside the designer and a description (D) of the artefact, respectively. The FBS ontology subsumes R in the notion of function and defines D as the external representation of a design solution:

(5) S → D

Based on the common observation that designing is not only a process of iterative, incremental development but frequently involves focus shifts, lateral thinking and emergent ideas, the FBS ontology defines the following additional transformations:

(6) S → S',

(7) S → Be', and

(8) S → F'

The eight fundamental transformations or processes in the FBS ontology are shown and labelled in Figure 2:

1. Formulation (R → F, and F → Be)
2. Synthesis (Be → S)
3. Analysis (S → Bs)
4. Evaluation (Be ↔ Bs)
5. Documentation (S → D)
6. Reformulation type 1 (S → S')
7. Reformulation type 2 (S → Be')
8. Reformulation type 3 (S → F')

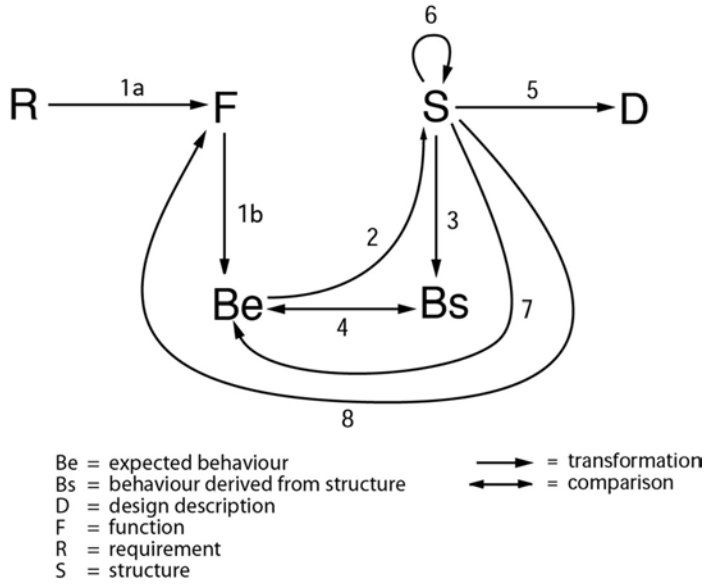


Figure 2. The FBS ontology defining eight fundamental processes in designing

5. Locating the Two Systems in the FBS Ontology

For locating the two systems of the dual-system theory in the FBS ontology, it is useful to begin with a simplified view of design thinking: as an input-output transformation, where the designer takes requirements as input and produces a design description as output. (The term "designer" is used here to encompass a single designer or a design team.) This is shown in Figure 3.

Figure 3. An input-output view of design thinking: A designer transforming requirements (R) into a design description (D)

The details of the transformation of R into D are hidden inside the designer that is viewed as a "black box" (indicated by the "+" symbol in Figure 3). In Figure 4 this black box is expanded to show possible pathways from R to D, using the processes defined in the FBS ontology. The entry and exit paths of this process system are the transformations of R into F (part of formulation, process 1) and of S into D (documentation, process 5), respectively. They

correspond to activities of interpretation and action that are executed by the designer.

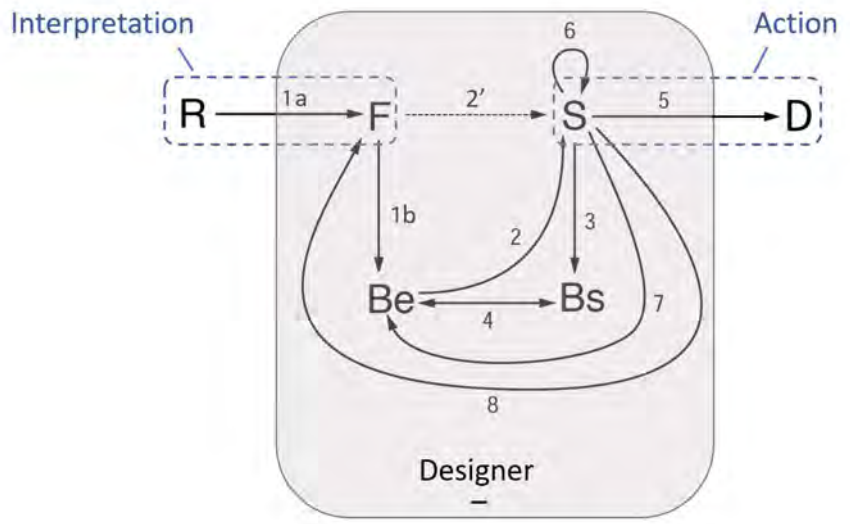


Figure 4. Expanding the transformation of R into D, based on the FBS ontology

While either of the two systems can occur in any of the processes, we focus system 1 thinking on the process that leads to the most reduction in cognitive load: F to S. Figure 4 represents a novel extension of the original FBS ontology, resulting from locating dual-system theory in it for F to S. In addition to the eight fundamental processes in the FBS ontology, a ninth process (2') is depicted that transforms F into S. This additional process allows distinguishing two basic pathways between the interpretation of R and the action producing D: (1) a direct pathway provided by process 2', and (2) an indirect pathway that involves at least four processes: 1b, 2, 3 and 4. Processes 3 and 4 are needed in the latter pathway based on the assumption that designing requires analysis and evaluation of the generated S prior to producing D.

Since 2' establishes a direct link between interpretation and action, it can be seen as a reflex – an immediate response to a stimulus without involving any form of reasoning. This corresponds to system 1. The reflex represented by process 2' is based on learning a connection between stimulus and response through previous experiences of the designer. Whenever a pattern in the environment is interpreted that matches a previous stimulus, the associated response is executed as an instant reflex. Examples of pattern matching in architectural design include designing using precedents (Clark and Pause 2005).

Process 2' can be thought of as subsuming the set of processes 1b, 2, 3 and 4, as is shown in Figure 5:

2' θ = {1b, 2, 3, 4} (1)

where θ is a substitution[1].

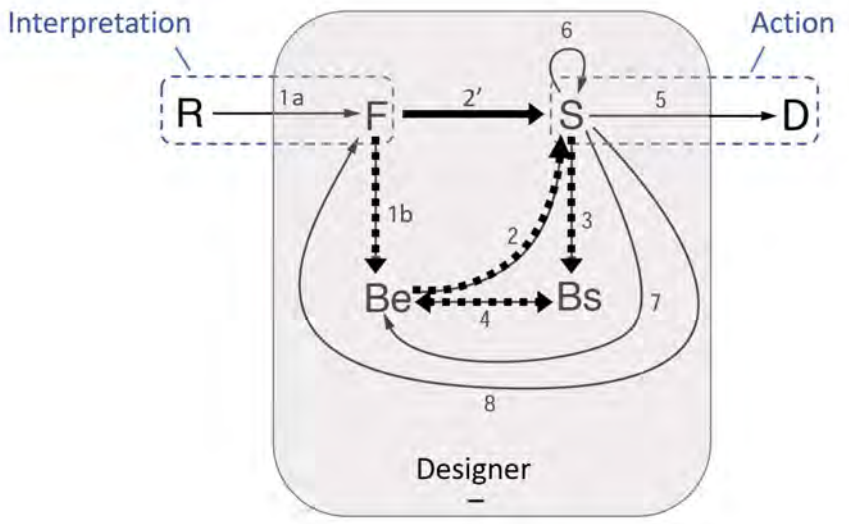


Figure 5. Process 2' (highlighted using a bold, solid arrow) subsumes processes 1b, 2, 3 and 4 (highlighted using bold, dotted arrows)

The new process is termed 2' to emphasise its principal role as a producer of synthesised S, even though it substitutes processes 1, 3 and 4 as well. It provides a shortcut for this quadruple of processes, using a learned connection between F and S. This increases cognitive efficiency when performing design tasks that address similar Fs. Learning the connection between F and S involves eliminating all intermediate processes that were previously used for transforming F into S. It compiles previous design processes, initially experienced as sequences of design decisions, into a post-hoc, explanatory account that "edits out false starts and imposes a spurious order on an indeterminate past" (Weick 1995). This distinction corresponds to Conklin and Yakemovic's (1991) notions of "structure-oriented" and "process-oriented" design rationale, respectively. The compilation of a design process into a single step, from F to S, can be seen as an extreme form of structure-oriented design rationale.

[1] X subsumes Y if and only if there is a substitution θ such that X θ = Y

Designing often involves a great deal of incompleteness and uncertainty: the requirements may be unclear, conflicting or incomplete, and the environment and its possible interactions with the artefact may be unknown. Process 2' can be a useful tool for commencing designing in these conditions, by providing heuristics (Gigerenzer and Goldstein 1996) to come up with design structures. The use of heuristics has been linked to creative concept generation (Yilmaz et al. 2015). However, designers should be wary of the fallacies of system 1 executing these heuristics (Bulleit 2013), as heuristic knowledge may be too simplified or based on insufficient information about the ranges of applicability. As system 1 is concerned only about the coherence but not the quality or robustness of the responses it generates, system 2 should become involved to avoid potentially serious design errors. It does so by monitoring the results of system 1. In the FBS ontology, this corresponds to processes 1b (setting expectations about the behaviour), 3 (analysing the structure) and 4 (comparing expected and actual behaviour). In case of failure of the generated structure (S) to meet the expectations, a new structure needs to be generated. This can be done in one of two ways: (1) by selecting the second most grounded pattern, or (2) by reformulating structure based on reflection (Schön and Wiggins 1992).

The first of the two ways of generating new structure is executed by system 1, because it is still based on pattern matching even though the most grounded pattern (which produced the failed S) is now "blocked". In the FBS ontology, this process is captured by applying process 2' iteratively. It can be viewed as a new attempt of system 1 to propose an S that is part of a pattern linked to F.

The second way of producing new S is by reformulation, which in the FBS ontology is represented by process 6. As it is a reflective process, it is executed by system 2. The relationship between processes 2' and 6 is again one of subsumption, with the necessary condition that there already pre-exists a structure, as highlighted in Figure 6:

$$(2' \; \theta = 6) \rightarrow \exists \; S^{prev} \qquad (2)$$

where S^{prev} is a previous structure.

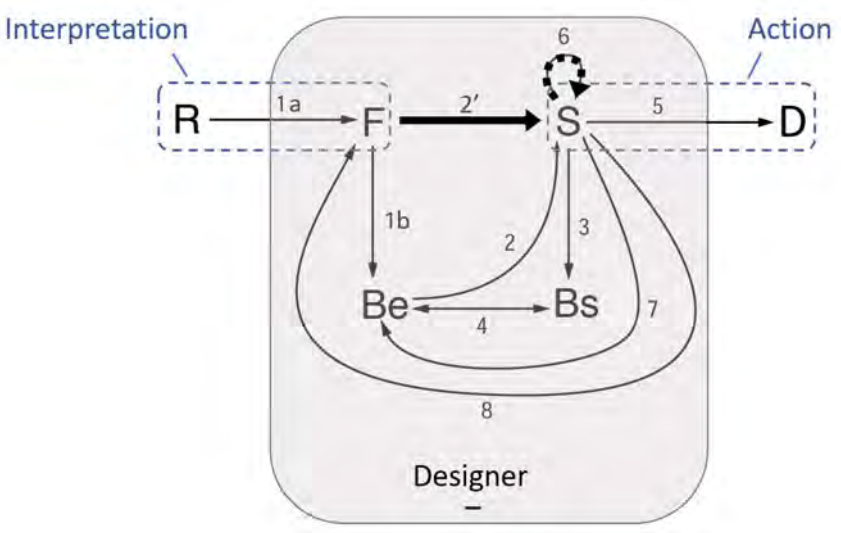


Figure 6. After failure of the initial S, process 2' (executed by system 1) can be used again by selecting the second most grounded pattern to be matched. Process 2' (bold, solid arrow) subsumes process 6 (bold, dotted arrow).

Process 2' can be executed iteratively, each time proposing a new structure that is first monitored and evaluated and, if it fails the evaluation, eventually replaced by another structure proposal. This corresponds to a process of search, in which a given (i.e. grounded) set of structure candidates is examined one by one, until a satisfactory candidate is found.

6. Instances of Fast and Slow Design Thinking

In this Section we illustrate the framework of fast and slow design thinking using four instances of designing: design fixation, case-based design, pattern language-based design and brainstorming. They were chosen for two reasons: First, they all include some aspects of fast, intuitive (system 1) thinking, as described in Section 3. This sets them clearly apart from mainstream models of designing that emphasise slow, analytical (system 2) thinking. Similar to Kahneman's book that is mainly about system 1 thinking, we see the main contribution of this paper in a better understanding of system 1 design thinking. The selection of the four instances of designing reflect this emphasis on system 1.

Second, the four instances are located within a wide spectrum of granularity where overlaps across instances may be possible. For example, design fixation may be found within case-based design, and brainstorming may be used as a means to reduce the effects of design fixation. Further, all instances may be used in conjunction with other (even mainstream) models of

designing not presented in this paper. They are related to routine design (design fixation, case-based design, pattern language-based design) and non-routine design (brainstorming). Based on their ubiquity in various models of design, the four instances cover a large range of design processes related to system 1 thinking.

6.1. DESIGN FIXATION

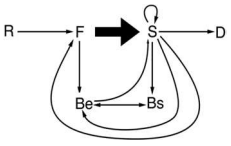
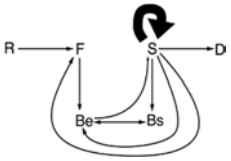
Design fixation is the premature commitment on a design concept early in the process of designing (Jansson and Smith 1991). This is often perceived as an obstacle for design creativity. Fixation has been attributed to an "overactive" system 2 (Moore et al. 2014) that aims to transform initial ideas in an analytic manner (Sowden et al. 2015) without considering alternative options. We can use the FBS ontology to describe the role of the two systems in design fixation in more detail.

Fixation starts with the generation of structure (S) (or its presentation to the designer by an external source; for example, as a precedent) as a potential solution to a design problem. For fixation to occur, it is assumed that the structure causing that fixation is highly grounded and there is a strong connection between F and S. In the FBS ontology, this corresponds to process 2' (i.e., system 1).

Once S has been produced, it is used as the basis for generating further structures that can be viewed as elaborations of the initial S (e.g. decompositions). This is represented by process 6. It includes analytic forms of reasoning executed by system 2.

The processes involved in design fixation are summarised in Table 2.

TABLE 2. Processes involved in design fixation

System 1	System 2	FBS representation
1. Generating an initial idea or concept		 Process 2'
	2. Elaborating the initial structure	 Process 6

6.2. CASE-BASED DESIGN

Case-based design is an application of the Artificial Intelligence (AI) technique of case-based reasoning in the design domain (Kolodner 1987; Maher et al. 1995). It is based on retrieving and adapting existing design cases stored in memory (also called "case base"). A design case is a specific past design episode including the problem, the solution and the process for arriving at the solution (Rosenman et al. 1991). Case-based design involves the following phases: problem anticipation, search, match, retrieve, select, modify and repair (Maher et al. 1995).

Problem anticipation: enriches the given information about the design problem (i.e. the requirements, R) with as much implicit information as possible. This is captured by process 1a in Figure 4.

Search, *match* and *retrieve*: This phase aims to find an appropriate design case, based on the problem description (in terms of F) and information associated with it within the design cases. This corresponds to process 2' that is executed by system 1.

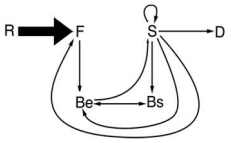
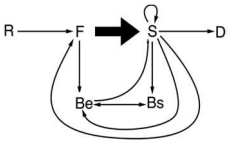
Select: determines the "best" matching design case among the retrieved ones. This can be represented using processes 3 and 4, as they are concerned with analysing and evaluating alternative designs.

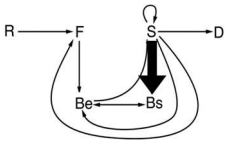
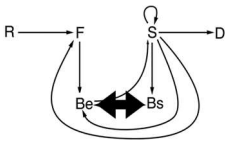
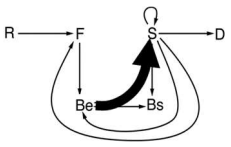
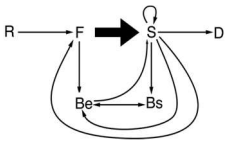
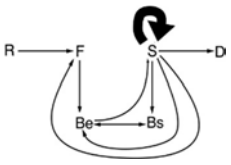
Modify: involves some adaptations of S to enhance the fit with the specific design situation at hand. This can be represented using process 2, where the new S is subsumed by the previous S.

Repair: is used after some performance failure of the design. This is done either by retrieving and selecting a different design case, or by modifying the existing design case. The former is captured by process 2' (i.e., system 1), the latter by process 6 (i.e., system 2). The new S produced by process 6 is subsumed by the previous S.

The processes involved in case-based design are summarised in Table 3.

TABLE 3. Processes involved in case-based design

System 1	System 2	FBS representation
	1. Problem anticipation: formulating implicit requirements	 Process 1a
2. Search, match and retrieve from existing case base		

		Process 2’
	3. Select the best matching design case	 Process 3  Process 4
	4. Modify S to establish a better fit with the design situation at hand	 Process 2
5a. Repair by retrieving and selecting S of a different design case	5b. Repair by generating new S based on the existing S	 Process 2’  Process 6

6.3. PATTERN LANGUAGE-BASED DESIGN

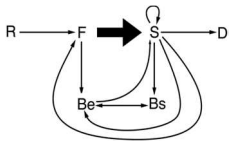
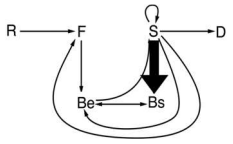
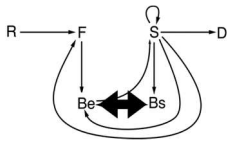
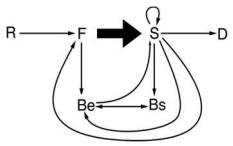
The concept of a pattern language was introduced by Alexander et al. (1977) in the architectural design domain and has since been applied in various other domains including software design (Gamma et al. 1995), process design (Lerner et al. 2010) and educational design (Goodyear 2005; Dehbozorgi et al. 2018). Patterns are descriptions of solutions to recurring problems,

including information about context and rationale. A pattern language is a representation of the interconnections between a collection of patterns.

Designing using a pattern language commences a search for potentially applicable patterns based on the problem represented as function (F). This search yields a pattern that contains a solution in terms of structure (S), leading to a direct transformation of F into S according to process 2' (which therefore is system 1 thinking). Considering the rationale included in the pattern, corresponds to processes 3 and 4 that are executed by system 1. In case a potential pitfall is identified, a new search is carried out to identify a pattern that addresses the pitfall as a problem. This can be viewed as a reformulation of structure by means of a new instance of process 2' (i.e., system 1).

The processes involved in pattern language-based design are summarised in Table 4.

TABLE 4. Processes involved in pattern language-based design

System 1	System 2	FBS representation
1. Selecting S using a search for applicable design patterns		 Process 2'
	2. Assess S based on the rationale included in the pattern	 Process 3  Process 4
3. Select a new pattern that addresses any evaluation failures		 Process 2'

6.4. BRAINSTORMING

Brainstorming is one of the most known creative design techniques (Cross 2000). It is based on bringing together a diverse group of people with a wide range of expertise and capturing their spontaneous ideas about a problem without assessing them.

A brainstorming session commences with the group leader formulating the problem statement. This can be represented as process 1a.

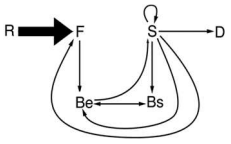
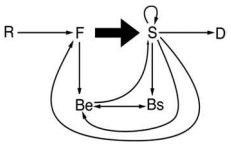
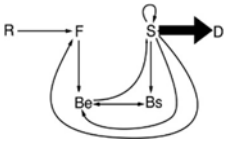
The group members then write down the first ideas that come to their minds. Every idea needs to be articulated succinctly so it fits on a small card. This corresponds to multiple instantiations of process 2' (executed by system 1).

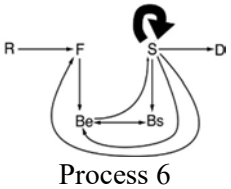
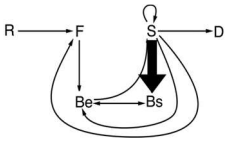
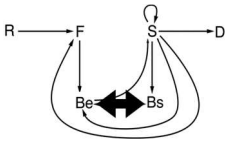
The next stage is the presentation of every idea to the group. No criticism or evaluation is allowed yet. The group rather reflects on the ideas, trying to develop them further or combining them. This can be viewed as process 6.

Only later does the group leader assess the ideas, which corresponds to processes 3 and 4.

The processes involved in brainstorming are summarised in Table 5.

TABLE 5. Processes involved in brainstorming

System 1	System 2	FBS representation
	1. Formulating a problem statement	 Process 1a
2. Write down spontaneous ideas		 Process 2'  Process 5

	3. Reflecting on the ideas, without criticising or evaluating	 Process 6
	4. Assessing the ideas	 Process 3  Process 4

7. Discussion

The four instances of designing illustrate the framework of system 1 and 2 design thinking developed in this paper. This set of instances is not exhaustive, as there are likely to be more instances where system 1 design thinking can be shown. However, even from the limited set of examples in this research, some lessons can be learned.

One insight can be derived from analysing the four instances of design processes. Three of them – design fixation, case-based design, and pattern language-based design – are instances of routine designing, and one of them – brainstorming – is an instance of non-routine (or creative) designing. Yet, in all of them system 1 plays a distinctive role. In routine designing system 1 merely reproduces existing design structures, while in non-routine designing it generates new design structures. This is consistent with Taura and Nagai's (2017) distinction between "experiential" and "associative" intuition and their respective effects on the creativity of the designs produced using these forms of intuition. It is also consistent with Kahneman's (2011) presentation of system 1, on the one hand, as a source of bias toward known experiences, and, on the other hand, as a "mental shotgun" that produces more (associative) concepts than it is asked for.

Another observation concerns the relationship between system 1 and system 2 design thinking. In all but one (namely, design fixation) of the four instances in Section 6, the results of system 1 executing process 2' are

subsequently analyzed (process 3) and evaluated (process 4). This is consistent with Kahneman's claim that system 2 monitors and assesses the decisions made by system 1.

The framework developed in this paper characterizes system 1 design thinking only as a transformation of F into S. This is because it is the activity with the highest cognitive load since it involves multiple processes – as a fast response of a designer producing a structure given a required function. This can be viewed as a black box, top-level model of system 1 in design. Yet, further characterizations are possible locating it on a more fine-grained level. For example, the evaluation of a design (process 4) may be carried out either fast or slow too. The same holds for the formulation of expected behaviours (process 1b), or any of the other eight fundamental processes.

8. Conclusion

Connecting dual-system theory with the FBS ontology of design contributes to the increasing body of research in aligning models of cognitive science and design science. The paper has shown that system 1 and system 2 thinking can be represented ontologically and mapped onto various instances of design thinking. Dual-system theory can be viewed as a meta-cognitive model of human thinking (Barr 2018), similar to the FBS ontology that is a meta-cognitive model of design thinking. They are generic and therefore independent of the specific domains or the specific instances of thinking and design thinking. This has the advantage that the specifics can be analysed, compared and discussed using a common terminology and common methods. Cross-domain and cross-instance insights can potentially be gained from such a uniform framework.

The combination of dual-system theory and the FBS ontology required an extension of the original FBS ontology, by adding a direct transformation of F into S. This does not represent a violation of the "no-function-in-structure" principle (De Kleer and Brown 1984). The new process (2') it is defined in this paper as a substitution of other processes in the ontology for reasons of cognitive efficiency. Yet, it originates from previous design experiences that originally proceeded from function to expected behaviour and then to structure.

Embedding process 2' in the existing FBS ontology has the benefit that empirical findings can now be better accounted for, especially the frequently observed direct transformation of F into S. For example, Yu and Gero (2016), using a Markov model analysis of design protocols in the context of parametric design, observed a high frequency of F-to-S transformations based on the use of design patterns. Having an explicit process representing this transformation opens up the possibility of revisiting other design protocols and analysing them for the occurrence of system 1 design thinking. This may

also empirically validate the ontological model of fast and slow design thinking presented in this paper. Initial results from design protocols of professional engineers and engineering students are available that confirm this model of design thinking that includes system 1 thinking (Kannengiesser and Gero 2019).

Future design research may use this work for developing new methods and tools for performing and teaching design. This is because it provides access to well-established findings in the various sub-disciplines of cognitive psychology. For example, methods for analysis and evaluation in design may benefit from cognitive approaches that help overcome the laziness of system 2 to avoid biased judgements due to system 1. This gap is shown in Section 6: Design fixation occurs because there is a lack of analysis (process 3) and evaluation (process 4) of the structure produced by process 2'. Therefore, research may develop tools that stimulate analysis and evaluation activities by system 2 and possibly feed the results back to system 1 for improved generation of structure in future design tasks.

Another possible extension of this work is to investigate the usefulness of Stanovich's (2009) "tri-process theory" for design thinking. This theory splits system 2 into two modes or processes: an algorithmic and a reflective process. The resulting set of three processes may be mapped onto Maher and Gero's (2002) reflexive, reactive and reflective modes of reasoning for situated design agents.

Early studies in applying the artificial intelligence technique of machine learning to design resulted in the encoding of B to S that today would be called system 1 design thinking (Gero and Marmot 1974). A new range of computational design tools based on deep learning (LeCun, Bengio and Hinton 2015) are under development and are all examples of system 1 design thinking. They find relationships between F and S and between B and S from large bodies of design data (McComb 2019).

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References

Alexander C, Ishikawa S, Silverstein M and Jacobson M (1977) *A Pattern Language: Towns, Buildings, Construction*, Oxford University Press, New York.

Badke-Schaub P and Eris O (2014) A theoretical approach to intuition in design: Does design methodology need to account for unconscious processes? *in* A Chakrabarti

and LTM Blessing (eds) *An Anthology of Theories and Models of Design*, Springer, pp. 353-370.

Barr N (2018) Intuition, reason, and creativity: An integrative dual-process perspective, *in* G Pennycook (ed.) *The New Reflectionism in Cognitive Psychology: Why Reason Matters*, Routledge, London, Chapter 6.

Bott MJ and Mesmer B (2019) Determination of function-behavior-structure model transition probabilities from real-world data, *AIAA Scitech 2019 Forum*, San Diego, CA.

Brown T (2009) *Change by Design: How Design Thinking Transforms Organizations and Inspires Innovation*, Harper-Collins, New York.

Bulleit WMB (2013) Engineers shouldn't think too fast, *Structures Congress 2013*, Pittsburgh, PA.

Clark RH and Pause M (2005) *Precedents in Architecture: Analytic Diagrams, Formative Ideas, and Partis*, John Wiley & Sons, Hoboken, NJ.

Conklin EJ and Yakemovic KCB (1991) A process-oriented approach to design rationale, *Human-Computer Interaction* **6**(3): 357-391.

Cross N (2000) *Engineering Design Methods: Strategies for Product Design*, John Wiley & Sons, Chichester.

Cross N (2001) Design cognition: results from protocol and other empirical studies of design activity, *in* C Eastman, W Newstetter, and M McCracken (eds) *Design Knowing and Learning: Cognition in Design Education*, Elsevier, Oxford, pp. 79-103.

Dehbozorgi N, MacNeil S, Maher ML and Dorodchi M (2018) A comparison of lecture-based and active learning design patterns in CS education, *International Conference on Frontiers in Education*, to appear

De Kleer J and Brown JS (1984) A qualitative physics based on confluences, *Artificial Intelligence* **24**(1-3): 7-83.

Eckert C (2013) That which is not form: The practical challenges in using functional concepts in design, *Artificial Intelligence for Engineering Design, Analysis and Manufacturing* **27**(3): 217-231.

Eisenbart B, Gericke K and Blessing LTM (2017) Taking a look at the utilisation of function models in interdisciplinary design: insights from ten engineering companies, *Research in Engineering Design* **28**(3): 299-331.

Eisenbart B and Kleinsmann M (2017) Implementing shared function modelling in practice: experiences in six companies developing mechatronic products and PSS, *Journal of Engineering Design* **28**(10-12): 765-798.

Evans JStBT and Stanovich KE (2013) Dual-process theories of higher cognition: Advancing the debate, *Perspectives on Psychological Science* **8**(3): 223-241.

Gamma E, Helm R, Johnson R and Vlissides J (1995) *Design Patterns: Elements of Reusable Object-Oriented Software*, Addison-Wesley, Reading, MA.

Gero JS (1990) Design prototypes: A knowledge representation schema for design, *AI Magazine* **11**(4): 26-36.

Gero JS (1999) Recent design science research: Constructive memory in design thinking, *Architectural Science Review* **42**(2): 97-99.

Gero JS and Kannengiesser U (2004) The situated function-behaviour-structure framework, *Design Science* **25**(4): 373-391.

Gero JS and Kannengiesser U (2012) Representational affordances in design, with examples from analogy making and optimization, *Research in Engineering Design* **23**(3): 235-249.

Gero JS and Kannengiesser U (2014) The function-behaviour-structure ontology of design, *in* A Chakrabarti and LTM Blessing (eds) *An Anthology of Theories and Models of Design: Philosophy, Approaches and Empirical Explorations*, Springer, pp. 263-283.

Gero JS and Marmot A (1974) Modelling elevator lobbies, *Building Science* **9**(4): 277-288.

Gero JS and Peng W (2009) Understanding behaviors of a constructive memory agent: A markov chain analysis, *Knowledge-Based Systems* **22**(8): 610-621.

Gigerenzer G and Goldstein DG (1996) Reasoning the fast and frugal way: Models of bounded rationality, *Psychological Review* **103**(4): 650-669.

Goodyear P (2005) Educational design and networked learning: Patterns, pattern languages and design practice, *Australasian Journal of Educational Technology* **21**(1): 82-101.

Hay L, Duffy AHB, McTeague C, Pidgeon LM, Vuletic T and Grealy M (2017) Towards a shared ontology: A generic classification of cognitive processes in conceptual design, *Design Science* **3**.

Howard TJ, Culley SJ and Dekoninck E (2008) Describing the creative design process by the integration of engineering design and cognitive psychology literature, *Design Studies* **29**(2): 160-180.

Jansson DG and Smith SM (1991) Design fixation, *Design Studies* **12**(1): 3-11.

Kahneman D (2011) *Thinking, Fast and Slow*, Penguin Books, London.

Kahneman D and Frederick S (2002) Representativeness revisited: Attribute substitution in intuitive judgement, *in* T Gilovich, D Griffin and D Kahneman (eds) *Heuristics and Biases: The Psychology of Intuitive Judgement*, Cambridge University Press, Cambridge, pp. 49-81.

Kannengiesser U and Gero JS (2012) A process framework of affordances in design, *Design Issues* **28**(1): 50-62.

Kannengiesser U and Gero JS (2017) Can Pahl and Beitz‘ systematic approach be a predictive model of designing?, *Design Science* **3**.

Kannengiesser U and Gero JS (2019) Empirical evidence for Kahneman’s System 1 and System 2 Thinking in Design, *Human Behaviour in Design 2019*, Tutzing, Germany, to appear

Kolodner JL (1987) Extending problem solver capabilities through case-based inference, *Proceedings of the Fourth International Workshop on Machine Learning*, pp. 167-178.

Lawson BR (1994) *Design in Mind*, Butterworth, London.

LeCun Y, Bengio Y and Hinton G (2015) Deep learning, *Nature* **521**: 436-444.

Lerner BS, Christov S, Osterweil LJ, Bendraou R, Kannengiesser U and Wise A (2010) Exception handling patterns for process modeling, *IEEE Transactions on Software Engineering* **36**(2): 162-183.

Liedtka J and Ogilvie T (2011) *Designing for Growth*, Columbia Business Press, New York.

Maher ML, Balachandran B and Zhang DM (1995) *Case-Based Reasoning in Design*, Lawrence Erlbaum Associates, Mahwah, NJ.

Maher ML and Gero JS (2002) Agent models of 3D virtual worlds, *ACADIA 2002*, California State Polytechnic University, Pamona, CA, pp. 127-138.

McComb C (2019) Toward the rapid design of engineered systems through deep neural networks, *in* JS Gero (ed.) *Design Computing and Cognition'18*, Springer, Dordrecht, pp. 3-20.

Moore D, Sauder J and Jin Y (2014) A dual-process analysis of design idea generation, *Proceedings of the ASME 2014 International Design Engineering Technical Conferences & Computers and Information in Engineering Conference IDETC/CIE 2014*, Buffalo, NY.

Pahl G and Beitz W (2007) *Engineering Design: A Systematic Approach*, Springer, Berlin.

Rosenman MA, Gero JS and Oxman RE (1991) What's in a case: the use of case bases, knowledge bases and databases in design, *in* GN Schmitt (ed.) *CAAD Futures'91*, ETH, Zürich, pp. 263-277.

Roth K (2000) *Konstruieren mit Konstruktionskatalogen: Band 2: Kataloge*, Springer-Verlag, Berlin.

Schön DA and Wiggins G (1992) Kinds of seeing and their functions in designing, *Design Studies* **13**(2): 135-156.

Simon HA (1969) *The Sciences of the Artificial*, MIT Press, Cambridge.

Sloman SA (1996) The empirical case for two systems of reasoning, *Psychological Bulletin* **119**(1): 3-22.

Sowden PT, Pringle A and Gabora L (2015) The shifting sands of creative thinking: Connections to dual process theory, *Thinking & Reasoning* **21**(1): 40-60.

Stanovich KE (2009) Distinguishing the reflective, algorithmic, and autonomous minds: Is it time for a tri-process theory? *in* JStBT Evans and K Frankish (eds) *In two minds: Dual processes and beyond*, Oxford University Press, New York, pp. 55-88.

Stanovich KE and West RF (2000) Individual differences in reasoning: Implications for the rationality debate? *Behavioral and Brain Sciences* **23**(5): 645-665.

Taura T and Nagai Y (2017) Creativity in innovation design: the roles of intuition, synthesis, and hypothesis, *International Journal of Design Creativity and Innovation* **5**(3-4): 131-148.

Ullman DG, Dietterich TG and Stauffer LA (1988) A model of the mechanical design process based on empirical data, *Artificial Intelligence for Engineering, Design, Analysis and Manufacturing* **2**(1): 33-52.

Verganti R (2009) *Design-Driven Innovation: Changing the Rules of Competition by Radically Innovating what Things Mean*, Harvard Business Press, Boston.

Wason PC and Evans JStBT (1975) Dual processes in reasoning? *Cognition* **3**(2): 141-154.

Weick KE (1995) *Sensemaking in Organizations*, Sage Publications, Thousand Oaks, CA.

Wynn DC and Clarkson PJ (2018) Process models in design and development, *Research in Engineering Design* **29**(2): 161-202.

Yilmaz S, Daly SR, Seifert CM and Gonzalez R (2015) How do designers generate new ideas? Design heuristics across two disciplines, *Design Science* **1**.

Yu R and Gero JS (2016) An empirical basis for the use of design patterns by architects in parametric design, *International Journal of Architectural Computing* **14**(3): 289-302.