

AN EXPLORATION OF DESIGN SYNTHESIS

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Abstract

Building on the contributions of existing works in the area of design ontology, this paper presents a hypothetical model of design synthesis which depicts design activities, design outputs and two modes of thought in design. The model is used as a basis upon which to explore design synthesis at multiple levels of cognitive granularity. Studies of conceptual design cognition lend support to a distinction between the creation of design elements and their composition. Additional studies of cognitive processing are reviewed and summarised in order to identify cognitive processes which might be involved in design composition. The review highlights several cognitive processes which have yet to be studied in an ecologically valid design context but which could form the basis of a multi-level model of design synthesis.

Keywords: Design cognition, Human behaviour in design, Conceptual design

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1 INTRODUCTION

Synthesis is widely acknowledged as being an important aspect of the engineering design and product design engineering processes. Books are dedicated to the subject (Antonsson and Cagan, 2005; Chakrabarti, 2002), process models describe its role in design (Howard et al., 2008; Wynn and Clarkson, 2005), computational models automate the process (Cagan et al., 2005), design ontologies define the activity (Gero and Kannengiesser, 2014; Sim and Duffy, 2003) and cognitive studies observe designers engaged in synthesis (Daly et al., 2012; Lane and Seery, 2011). Yet despite the obvious involvement of 'synthesis' in design there is presently no unified understanding of the phenomenon in the design literature. Across most existing accounts of synthesis, it appears that very little is known about the cognitive processes involved.

Beyond the field of design there are a number of phenomena involving cognitive combination processes that have clear similarities to various accounts of design synthesis. The term 'synthesis' in the context of creative cognition (Finke et al., 1992) refers to the mental process of combining parts into more mature wholes. A similar process, conceptual combination, deals with the mental combination and interpretation of word pairs which represent category concepts. While the relevance of mental synthesis to the design process has previously been acknowledged (Purcell and Gero, 1998); conceptual combination and its associated cognitive processes has received relatively little attention. What's more, only limited efforts have been made to make explicit mappings between design activities and cognitive processes (see: Jin and Chusilp, 2006).

There is an opportunity for a novel perspective on design synthesis developed purposefully to describe both design activities and the cognitive processes involved in them. Towards this aim it is necessary to consider design synthesis at multiple levels of cognitive granularity and to look beyond the field of design for evidence of cognitive processing in related phenomena.

2 DESIGN SYNTHESIS

Etymologically, synthesis is the combining, assembling or mixing of something into a new whole, and it has been noted that synthesis in design can be loosely thought of as the generation of solutions to problems (Roozenburg 2002). In the context of engineering design, Antonsson & Cagan (2005) describe synthesis as “the creative step itself: the conception and postulation of possibly new solutions to solve a problem” (p. xvii). Chakrabarti (2002) collates five overlapping definitions of synthesis in engineering design. Within these definitions, authors are seen to describe synthesis as narrowly as generation and decision in response to a problem (Finger & Rinderle 2002) or as broadly as being synonymous with design itself (Tomiyama et al. 2002).

Models of the design process reflect this lack of agreement in definition, portraying synthesis either as a distinct phase within an essentially linear design process, or as a recurring part of the problem-solving process. Regarding the former, Wynn & Clarkson (2005) describe a number of abstract, problem-oriented models, in which emphasis is placed on abstraction and analysis of the problem before the subsequent generation and evaluation of solutions. One such model describes the design process as three linear stages of analysis, synthesis and evaluation, where 'synthesis' is synonymous with the generation of solutions (Jones, 1963). This is similar to the four stage model by Cross (1994) which does not use the term 'synthesis', but includes a generation stage in which the designer produces solutions. Archer (1965) proposes a systematic, procedural approach to design, which is more specific than the previous models. Six main phases of design are defined, where synthesis is the “preparation of outline design proposals” (Evbuomwan et al., 1996, p. 307) which follows analysis and precedes development. In a comparison of engineering design process models, (Howard et al., 2008) equates the 'synthesis' (Archer, 1984) and 'generation' (Cross, 2008) stages of the design process with 'concept generation'. Synthesis then, when viewed as part of a linear process, is a stage of design concerned with the generation of solutions or production of proposals which has some sequential relationship with analysis, evaluation and/or development.

An alternate view of synthesis places it within a problem solving process which occurs at every stage of the design process. Asimow, (1962) models the design process in terms of two dimensions, a vertical one which involves sequential phases of the design process (Feasibility study, Preliminary design, detailed design), and a horizontal one in the form of an analysis-synthesis-evaluation-decision-optimisation-revision cycle. This horizontal dimension repeats at each phase of the process

(Evbuomwan et al., 1996). Roozenburg and Cross, (1991) describe this two dimensional representation of design as typical of “what might be called a consensus model” (p. 215), a convergence of theory which despite being described differently by various authors e.g. Pahl & Beitz (1996), generally portrays engineering design in the same way. In this sense synthesis is not a stage of design but rather a recurring element of problem solving, not restricted to the concept generation stage but still related to analysis and evaluation.

Despite some degree of convergence within the field, there is no clear definition of synthesis in design generally, or engineering design specifically. Notably, these process model accounts of synthesis do not describe the specific behaviours which designers exhibit during synthesis, nor do they consider the cognitive processes involved in such behaviours. A comprehensive account of the cognitive processing involved in synthesis may be a valuable step towards a stable definition of design synthesis.

2.1 Design activity ontologies

In response to conflicting definitions of various activities within the design process, several authors have acknowledged the need for a shared understanding of designing (Gero and Kannengiesser, 2014; Sim and Duffy, 2003), and through efforts to construct such a consensus (i.e. an ontology), work has been done towards achieving a specific and operational definition of design synthesis.

The Function-Behaviour-Structure (FBS) ontology and its associated frameworks define design activities as transformations which occur between instances of reasoning about the Function, Behaviour and Structure properties of a design artefact (Gero and Kannengiesser, 2004, 2014). According to the FBS framework, synthesis is the instantiation of an expected behaviour into a structure capable of exhibiting said behaviour.

The situated Function Behaviour Structure framework (Gero and Kannengiesser, 2004, 2014) extends this description of the same instantiation process across multiple 'worlds' by accounting for the situated nature of design and the notion of constructive memory. Synthesis begins with the designer “deciding” (Gero and Kannengiesser, 2014, p. 272) on the Structure (S) variables expected to be capable of instantiating a behaviour, before then externalising them via an action process. This can take the form of a drawing, creation of a CAD model or construction of a physical prototype (Gero and Kannengiesser, 2014). Thus, synthesis is said to involve a decision in the designers expected world, and an externalisation process into the external world.

An alternative account of design activities is provided by Sim & Duffy (2003) who describe synthesis as a compound activity comprised of 9 subordinate activities. The goal of synthesis is a final design which satisfies all the design requirements and contains sufficient detail for manufacture. Synthesis in this case involves the "search, exploration and discovery of design solutions, and composition and integration of these solutions" (Sim and Duffy, 2003, p. 205). The nine activities which comprise synthesis are defined in terms of knowledge transformations which increase the detail or the concreteness of the design artefact.

Both the FBS frameworks (Gero and Kannengiesser, 2014) and the taxonomy of design synthesis activities (Sim and Duffy, 2003) present operational definitions of synthesis, thereby addressing the lack of clarity present in previous synthesis definitions (Section 2). The FBS frameworks provide a valuable formalism of the relationship between synthesis, analysis and evaluation activities, however the activities themselves are general and describe a broad range of possible behaviours. In contrast, the design definition taxonomy presents a more specific description of the activities thought to be involved in synthesis. Unlike the FBS frameworks however, the design synthesis taxonomy does not describe the interplay between synthesis and the additional classes of activity which it accompanies, in this case evaluation and management.

The complementary strengths of each of these accounts can be used as a starting point for a new viewpoint on design synthesis. Notably, although each account provides significant insight into design activities, neither offers a low-level description of the cognitive processes associated with each activity, perhaps due to the limitations of the protocol study method used to validate them.

3 A HYPOTHETICAL MODEL OF DESIGN SYNTHESIS

The previous sections have reported on some strengths and limitations of existing accounts of design synthesis. This research does not claim to deliver a unified or comprehensive definition of synthesis; rather the aim is to build upon existing research to produce a description of some of the design activities

thought to be involved in design synthesis in addition to their cognitive processes. This aim will be achieved by presenting a hypothetical description of design synthesis at the design activity level, evaluating that perspective, and expanding it to account for cognitive processing. Evaluation is required to test the hypothetical representation proposed in Figure 1 and expansion is required to identify cognitive processes which might be involved in the proposed design activities. These steps will be achieved through (i) critical comparison against existing literature and (ii) empirical studies of designers in practise.

A hypothetical model is proposed (Figure 1) which depicts design outputs (grey nodes, capitalised) and design activities (*between* and *at* grey nodes, lower case) involved in conceptual design synthesis. Design activities at nodes give rise to the design output within the node. This initial instantiation attempts to: (i) capture the relationship between analysis, synthesis and evaluation as per design process models (Section 2) and the FBS ontology (Gero and Kannengiesser, 2004), (ii) distinguish between the composition of design concepts and the creation of new design concepts, and (iii) show that the inputs to the 'compose' activity can be existing concepts collected via a search process, or newly created concepts produced through some creation process.

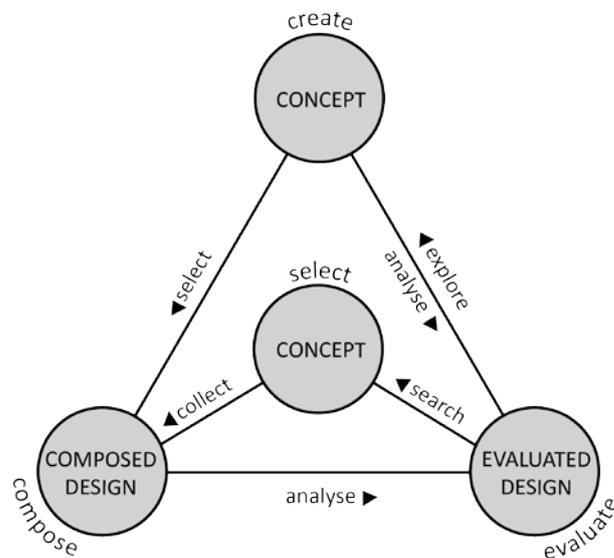


Figure 1 - A model of exploratory design synthesis

The model proposes a distinction between design concepts already present within the design process, and those which need to be created. The former can be searched for, selected and collected in response to evaluation of the present design state; the latter are the result of exploration and creation. Though presently unspecified, such exploration may take the form of retrieval from memory, analogical transfer, or a structured concept generation technique. Regardless of its source, all concepts can be composed into more elaborate designs. Analysis can be carried out either on composed designs or on created designs, producing behaviour which can be evaluated.

The model currently represents design activities at a singular level of cognitive granularity. That is, all activities in the model are assumed to consist of overt behaviours which are identifiable in protocol. Figure 1 does not yet make any claims about the cognitive processes involved in these activities.

The broader aims of the present research represent a significant undertaking; as such, the remainder of this paper reports on a range of findings from literature intended to evaluate and expand the 'compose' activity. The model will be used as a platform against which to situate complimentary design cognition and cognitive psychology research.

4 COMPOSITION AND COGNITIVE PROCESSES IN DESIGN SYNTHESIS

A literature review is conducted with the dual aims of evaluating the role of the 'compose' activity within the model and identifying cognitive processes which are thought to be, or which may potentially be involved in the compose activity. Composition is defined and then multiple perspectives on the activity are presented.

4.1 Design concept combination

The distinction between the generation and composition of design concepts is based on the taxonomy of design synthesis activities (Sim and Duffy, 2003), where the 'compose' activity is defined in terms of the knowledge transformations shown in table 1. Composing is taken to be synonymous with combining and is described as either the combination of design concepts into a complete conceptual design, or modules into modular products. 'Compose' is closely linked with 'generate' and together they comprise the compound activity 'concept generation'. While the 'generate' activity produces concepts which fulfil individual function requirements, the output of 'compose' is said to be concepts which "satisfy the overall functions" (Sim and Duffy, 2003, p. 209).

Table 1 – Composing (Sim and Duffy, 2003)

Goal of design activity (Gd)	Input knowledge (Ik)	Knowledge output (Ok)	Knowledge change
<ul style="list-style-type: none"> Combine ideas/concepts through association of ideas/concepts that satisfy overall function 	<ul style="list-style-type: none"> Domain knowledge Combination tables, function modules 	<ul style="list-style-type: none"> Concepts or modules that satisfy the overall functions 	<ul style="list-style-type: none"> Knowledge of function to means structure Modular architecture

The composition of concepts is studied further by Nagai et al. (2009) who study the combination of concepts such as *ship* and *guitar*, represented by words, to produce design concepts in an unconstrained generation experiment. The combination of design concepts can be seen to be prescribed during numerous design methods e.g., brainstorming, mindmapping (6/3/5 method), morphological analysis and SCAMPER (Boeijen et al., 2014). It can be seen then, that composition activities have been identified in protocol, studied experimentally and are prescribed in design methods, yet none of these studies incorporate findings from cognitive design studies.

4.2 Cognitive processes in concept composition

A number of different views on synthesis can be identified from protocol studies of conceptual design cognition. Table 2 compares design activities from Sim and Duffy, (2003) with design activities and associated cognitive processes identified in protocol studies of conceptual design (Hay et al., 2016). Literature is organised in the table depending on whether the study is interpreted to address [a] conceptual design generally, [b] 'concept generation', or [c] distinct generation and composition processes. Sim and Duffy's 'generate' activity is included due to its compound relationship with 'compose'.

The term 'synthesis' is used uniquely in three instances: (i) 'synthesis' as per FBS (McNeill et al., 1998), (ii) synthesis as a heuristic component of concept generation (Lane and Seery, 2011), and (iii) synthesis as synonymous with the composition of design concepts (Daly et al., 2012). Viewpoint (iii) is also interpreted to be synonymous with 'assembly' (Kruger and Cross, 2006) and 'compose' (Jin and Chusilp, 2006). Notably, Jin and Benami, (2010) claim that a fourth form of synthesis (referring to mental synthesis, (Finke et al., 1992)), is not identifiable in protocol and do not report on its role in conceptual design.

Of those studies which identify design phenomenon comparable to the compose activity, only one is seen to describe a relationship which could be interpreted as a mapping of cognitive processes to design activities. The model of mental iteration in conceptual design (Jin and Chusilp, 2006) describes four design activities, two of which (generate and compose) have associated design sub-activities. These sub-activities are derived from the cognitive processes identified in Jin and Benami, (2010), which are in turn derived from Geneplore model of creative cognition (Finke et al., 1992). Despite the change in terminology from "cognitive processes" (Jin and Benami, 2010) to "sub-activities" (Jin and Chusilp, 2006, p. 30), this relationship is unique in that it represents a hierarchical cognitive mapping. According to their account, composing ideas involves the 'associate' and 'transform' cognitive processes, while generating ideas involves the processes 'perceive' and 'retrieve'.

Table 2 - Design activities and cognitive processes in protocol studies of conceptual design

	Design activity (Sim and Duffy, 2003)	Observed design activity	Associated cognitive processes	Author(s), Year
[a]	N/A (Conceptual design generally)	Not specified	Association	(Jin and Benami, 2010)
			Transformation	(Jin and Benami, 2010; Lane and Seery, 2011; Leblebici-Basar and Altarriba, 2013)
			Retrieval	(Jin and Benami, 2010; Lane and Seery, 2011)
			Perception	(Jin and Benami, 2010)
		“Synthesis”	-	(McNeill et al., 1998)
[b]	Concept generation (compound: generate and compose)	“Concept generation”	Transformation	(Lane and Seery, 2011)
			Retrieval	(Lane and Seery, 2011)
			Synthesis	(Lane and Seery, 2011)
[c]	Generating	“Generation”	-	(Kruger and Cross, 2006)
		“Generate”	Perceive Retrieve	(Jin and Chusilp, 2006)
	Composing	“Synthesise”	-	(Daly et al., 2012)
		“Assembly”	-	(Kruger and Cross, 2006)
		“Compose”	Associate Transform	(Jin and Chusilp, 2006)

Taken together, these studies demonstrate a lack of consensus regarding the definition of 'synthesis' in design cognition research, thus reflecting the same lack of clarity among design process models (Section 2). Several studies do however support the proposal that composition should be treated as a discrete activity as per Sim and Duffy, (2003). From this literature, it appears that limited work has been done to identify the cognitive processes involved in the composition of design concepts. Since these are all protocol studies, it is unclear whether this reflects the broader state of design cognition knowledge or is indicative of a limitation in the protocol study method.

4.3 Cognitive processes in non-design composing activities

Despite inconsistent use of the term 'synthesis', several authors have been seen to describe a combination-based design activity, however there is only limited knowledge concerning the cognitive processes involved in it. Two additional combinatorial phenomena are reviewed towards the goal of identifying cognitive processes which might be applicable to design composition. These are the previously identified mental synthesis process and the linguistic conceptual combination process.

4.3.1 Mental synthesis

The Geneplore model (Finke et al., 1992) provides a general account of the cognitive processes involved in creative invention. The model describes creative thought as two reciprocating phases of generation and exploration. Synthesis' in the context of the Geneplore model refers to *mental* synthesis, i.e. the mental arrangement or combination of concepts into more complex ones. Finke & Slayton (1988) developed the figural combination paradigm to study mental synthesis. These experiments tasked participants with combining geometric forms to create new, meaningful shapes which correspond to different categories. The paradigm has been employed in various forms to investigate how creativity can be improved through the manipulation of various constraints (Anderson and Helstrup, 1993; Finke et al., 1992; Finke and Slayton, 1988). The tasks used in these studies are comparable to design composition in the sense that component parts are combined to create new concepts, the output of which must satisfy some constraint (see: Table 1). However, while the paradigm is useful for investigating factors affecting creativity during mental synthesis, the experiments are based on an *a priori* definition of synthesis and involve the arrangement and reinterpretation of component parts, but not the manipulation of those individual parts.

In a study of synthesis and sketching behaviour, again using geometric forms, Verstijnen et al., (1998) identify two forms of synthesis: combination-without-modification and restructuring. Previous works demonstrated that sketching does not aid mental synthesis via figural combination (Anderson and Helstrup, 1993) but does aid figure-ground reversal (Chambers and Reisberg, 1985) and part-whole detection (Reed and Johnsen, 1975). Verstijnen et al., (1998) hypothesised that while the figural combination task involves the arrangement of initially separate parts, the other tasks required restructuring of the presented stimuli. Results from a part-whole detection task and a modified version of the figural combination paradigm showed differential effects of sketching on task performance, thus indicating two distinct forms of processing. While combining parts is relatively easy and can be done in mental imagery alone, restructuring is more difficult and can be improved in experts through sketching. The same paradigm has yet to be applied using design concepts as stimuli.

Pearson et al., (1999) investigate the involvement of components of the working memory model (Baddeley, 2012). Results over three studies demonstrate the involvement of spatial working memory during mental synthesis. Additionally, the authors argue that when component parts are presented to the participants verbally, verbal representations remain in the articulatory loop during synthesis to serve as a back-up for visual imagery used during synthesis. The authors conclude that mental synthesis appears to be distributed across working memory and is not localised solely in the visuo-spatial sketchpad. Again, the role of working memory components in design composition is currently unknown.

These studies indicate that there may be more cognitive processes beyond 'associate' and 'transform' involved in design synthesis. The role of these processes in design synthesis is currently unknown, thus presenting opportunities for further research. An issue with all the previously reported studies however is that the 2D and 3D geometric forms are not representative of the concepts used in design combination. This is an issue addressed by Barquero and Logie, (1999) who argue that the semantic properties of the parts being combined during synthesis affect the success of creative insight.

4.3.2 Linguistic conceptual combination

Designers reason about artefacts in terms of their function, behaviour and structure properties (Gero, 1990; Gero and Kannengiesser, 2004). Thus, additional knowledge is required regarding how the properties of a design concept influence the design composition process. Conceptual combination is an interpretation process in which a pair of concepts, typically represented by words, are mentally combined by an individual to create a new entity (Ward et al., 1997). Words can be interpreted in different ways depending on their context, and different types of interpretation involve different types of cognitive processing. The dual-process model of conceptual combination (Wisniewski, 1997) describes two forms of cognitive processing. For example, *corn-oil* is interpreted as oil which is made from corn; this is a property transfer interpretation and is carried out via a comparison and alignment process. However *lamp-oil* can mean oil for lighting lamps; this is a relational interpretation carried out via a scenario creation process (Wisniewski, 1997).

The comparison process is based on structural alignment theory (Gentner and Markman, 1997). Properties are transferred from a modifier concept to a head concept by aligning their representational structures, comparing them to identify the commonalities and differences between them, selecting properties of the modifier concept to be transferred to the head, and constructing a new version of the head concept which accommodates the new property. Thus, the comparison process is said to involve: selection, alignment and comparison, and construction. Parallel to this, a 'scenario creation' process combines two concepts by creating a thematic relation between them (Gagné and Shoben, 1997).

Although conceptual combination is fundamentally a linguistic interpretation process, these cognitive processes may have some bearing on design composition. What's more, comparison and alignment are also said to be involved in a variety of cognitive tasks such as analogy, decision making and similarity judgements (Wisniewski and Middleton, 2002). Owing to the ubiquity of these processes, their potential involvement in design synthesis warrants further investigation.

5 COMPARISON AGAINST MODEL AND FUTURE WORK

This paper has reported on findings from a literature review towards the aims of (i) evaluating the proposed 'compose' activity and (ii) identifying a range of cognitive processes which may be involved in the compose activity to expand the model. With regards to the first aim, four aspects of the model directly related to the compose activity are evaluated here:

1. **The ‘compose’ activity is distinct from the activity of creating new concepts** - A number of cognitive studies of conceptual design are seen to identify a combinatorial process distinct from the 'generation' of concepts (Daly et al., 2012; Jin and Chusilp, 2006; Kruger and Cross, 2006), thereby supporting the distinction between creation and combination activities in the proposed model. The 'create' activity in the proposed model appears to be synonymous with the generation of concepts and would benefit from being redefined as 'generate'.
2. **Composition can occur immediately following the creation of a new concept.** Jin and Chusilp, (2006) model a sequential move from idea generation to concept composition. Contrary to this however, Kruger and Cross, (2006) model evaluation immediately following generation of partial solutions. Notably, neither study explicitly defines a 'select' process. Further empirical evaluation is required to confirm this aspect of the model. It is possible that the proposed ‘select’ activity is being confounded with evaluation.
3. **Following evaluation, a designer can search for, select and collect existing concepts to be combined** - evaluation is seen to precede the composition processes identified by Kruger and Cross, (2006) and Jin and Chusilp, (2006), thus lending additional support to a link between from evaluation to composition. However, only (Jin and Chusilp, 2006) distinguish between the composition of newly generated concepts and existing concepts and neither model explicitly describes a search, selection or collection process. The inclusion of select and collect as design activities is currently unsupported and requires further investigation.
4. **Analysis and evaluation occur following the composition of concepts** – both models report on evaluation following the combination of concepts but make no explicit reference to an intermediary analysis process. This lends support for the link between 'compose' and 'evaluate', however the role of analysis requires further investigation.

Taken together, there is support for the distinction between creation and composition activities. The model of mental iteration in conceptual design (Jin and Chusilp, 2006) provides partial support for two claims of the proposed model: (i) the link from ‘evaluate’ to ‘compose’ (although the involvement of search, selection and collection processes is unsubstantiated), and (ii) the direct link between ‘create’ (or generate) and ‘compose’. The proposed sequential relationship between analysis and evaluation is currently unsupported, resulting in a mismatch with the claims of the FBS framework (Gero, 1990).

With regards to future expansion of the model, potentially relevant cognitive processes have been identified in two analogous combinatorial phenomena: mental synthesis and conceptual combination. Table 3 summarises the these processes:

Table 3 - Cognitive processes associated with composition activities

Authors	Phenomenon	Cognitive processes
(Jin and Chusilp, 2006)	Designers engaged in conceptual design	Associate Transform
(Finke et al., 1992)	Mental synthesis (Figural combination)	Mental synthesis
(Verstijnen et al., 1998)	Mental synthesis (Figural combination) (Part whole detection)	Combining Restructuring
(Wisniewski, 1997) (Estes, 2003) (Wilkenfeld and Ward, 2001)	Conceptual combination	Selection Alignment and Comparison Construction Scenario-creation
(Pearson et al., 1999)	Mental synthesis (Figural combination)	Involvement of spatial working memory Involvement of articulatory loop

Of notable consequence for the expansion of the proposed model is the evidence for a composition design activity (Table 2) and combination cognitive processes (Table 3). Only two cognitive processes have explicitly been mapped to the design activity 'compose', namely 'associate' and 'transform' (Jin and Chusilp, 2006), and it is currently unknown as to whether these processes provide a comprehensive description of the cognitive activity involved in design composition. The Geneplore model, however, treats association, transformation and (mental) synthesis as three distinct processes, thus suggesting that

there may be a discrete cognitive composition process at the core of the 'compose' design activity which has yet to be formalised. If this is the case then such a process could be further distilled into two separate processes. Verstijnen et al., (1998) distinguish between combination without modification and combination where the constituent parts are restructured. Similarly, (Wisniewski, 1997) describes a relational process which combines concepts without modification, and a property transfer process in which the concepts are modified and a new concept is constructed. If the composition of geometric forms and lexically represented category concepts involve comparable streams of dual-processing then perhaps the same might apply for the composition of design concepts.

The dual-process model also describes a selection process which refers to the selection of concept properties; this is not addressed in the figural combination paradigm likely because the task instructions require the entirety of the component parts to be used during synthesis. This suggests that the proposed model needs to be expanded to include not only the selection of design concepts, but the lower-level process of selecting properties to be used in composition.

As it stands the proposed model can be expanded to include three hypothetical aspects: a discrete cognitive composition process at the core of the compose design activity, a further distillation of said process into relational and restructuring processes, and the addition of a property selection process.

Based on the findings reported here, further evaluation of the model will be achieved in three ways. through (i) critical comparison of the remaining elements of the model against literature, (ii) development of a coding scheme to evaluate the model via protocol analysis, and (iii) ecologically valid experimental investigation of the three hypothetical cognitive processes highlighted above.

6 CONCLUSION

A hypothetical model of design synthesis has been proposed which builds upon existing work in the area of design ontology. Key features of the model are (i) the relationship between analysis, synthesis and evaluation activities, (ii) the treatment of composition as an activity distinct from generation, and (iii) the distinction between the search for known solutions and generation of new concepts as the result of creative thought.

Evaluation against literature has found mixed degrees of support for these claims, however no evidence has yet been found which supports the formalisation of search, selection or collection processes. Towards the aim of expanding the model, numerous cognitive processes have been identified which are currently associated with combination-based non-design activities; the involvement of these processes in design combination activities will be investigated pending future experimental work.

REFERENCES

- Anderson, R.E. and Helstrup, T. (1993), "Visual discovery in mind and on paper", *Memory & Cognition*, Vol. 21 No. 3, pp. 283–293.
- Antonsson, E.K. and Cagan, J. (2005), *Formal Engineering Design Synthesis*.
- Archer, L.B. (1984), "Systematic Method for Designers. In N. Cross", *Developments in Design Methodology*, The Design Council, London.
- Asimow, M. (1962), *Introduction to Design*, Prentice-Hall.
- Baddeley, A. (2012), "Working Memory: Theories, Models, and Controversies", *Annual Review of Psychology*, Vol. 63 No. 1, pp. 1–29.
- Barquero, B. and Logie, R.H. (1999), "Imagery Constraints on Quantitative and Qualitative Aspects of Mental Synthesis", *European Journal of Cognitive Psychology*, Vol. 11 No. 3, pp. 315–333.
- Boeijen, A. van, Daalhuizen, J., Zijlstra, J., Schoor, R. van der, Technische Universiteit Delft. Faculteit van het Industrieel Ontwerpen, van Boeijen, A., Daalhuizen, J., et al. (2014), *Delft Design Guide: Design Methods*.
- Cagan, J., Campbell, M.I., Finger, S. and Tomiyama, T. (2005), "A Framework for Computational Design Synthesis: Model and Applications", *Journal of Computing and Information Science in Engineering*, American Society of Mechanical Engineers, Vol. 5 No. 3, p. 171.
- Chakrabarti, A. (Ed.). (2002), *Engineering Design Synthesis*, Springer London, London, available at: <https://doi.org/10.1007/978-1-4471-3717-7>.
- Chambers, D. and Reisberg, D. (1985), "Can mental images be ambiguous?", *Journal of Experimental Psychology: Human Perception and Performance*, American Psychological Association, Vol. 11 No. 3, pp. 317–328.
- Cross, N. (2008), *Engineering Design Methods : Strategies for Product Design*, J. Wiley.
- Daly, S.R., Yilmaz, S., Christian, J.L., Seifert, C.M. and Gonzalez, R. (2012), "Design Heuristics in Engineering", Vol. 101 No. 4, pp. 601–629.

- Estes, Z. (2003), "Attributive and relational processes in nominal combination", *Journal of Memory and Language*, Vol. 48 No. 2, pp. 304–319.
- Evbuomwan, N.F.O., Sivaloganathan, S. and Jebb, A. (1996), "A Survey of Design Philosophies, Models, Methods and Systems", *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture*, Vol. 210 No. 4, pp. 301–320.
- Finke, R.A. and Slayton, K. (1988), "Explorations of creative visual synthesis in mental imagery", *Memory & Cognition*, Springer-Verlag, Vol. 16 No. 3, pp. 252–257.
- Finke, R.A., Ward, T.B. and Smith, S.M. (1992), "Creative cognition: Theory, research, and applications", p. 239.
- Gagné, C.L. and Shoben, E.J. (1997), "Influence of Thematic Relations on the Comprehension of Modifier–Noun Combinations", *Journal of Experimental Psychology. Learning, Memory, and Cognition*, American Psychological Association, Vol. 23 No. 1, pp. 71–87.
- Gentner, D. and Markman, A.B. (1997), "Structure mapping in analogy and similarity", *American Psychologist*, Vol. 52 No. 1, pp. 45–56.
- Gero, J.S. (1990), "Design Prototypes: A Knowledge Representation Schema for Design", *AI Magazine*, Vol. 11 No. 4, p. 26.
- Gero, J.S. and Kannengiesser, U. (2004), "The situated function–behaviour–structure framework", *Design Studies*, Vol. 25 No. 4, pp. 373–391.
- Gero, J.S. and Kannengiesser, U. (2014), "The Function-Behaviour-Structure Ontology of Design", *An Anthology of Theories and Models of Design*, Springer London, London, pp. 263–283.
- Hay, L., McTeague, C., Duffy, A.H.B., Pidgeon, L.M., Vuletic, T. and Grealy, M. (2016), "A systematic review of protocol studies on conceptual design cognition".
- Howard, T.J., Culley, S.J. and Dekoninck, E. (2008), "Describing the creative design process by the integration of engineering design and cognitive psychology literature", *Design Studies*, Vol. 29 No. 2, pp. 160–180.
- Jin, Y. and Benami, O. (2010), "Creative patterns and stimulation in conceptual design", *Artificial Intelligence for Engineering Design, Analysis and Manufacturing*, Vol. 24 No. 2, p. 191.
- Jin, Y. and Chusilp, P. (2006), "Study of mental iteration in different design situations", *Design Studies*, Vol. 27 No. 1, pp. 25–55.
- Jones, J.C. (1963), "A method of systematic design", *Conference on Design Methods*, Pergamon Press, Oxford/New York, pp. 53–57.
- Kruger, C. and Cross, N. (2006), "Solution driven versus problem driven design: strategies and outcomes", *Design Studies*, Vol. 27 No. 5, pp. 527–548.
- Lane, D. and Seery, N. (2011), "Examining the development of sketch thinking and behaviour", *Annual Conference for the American Society of Engineering Education*.
- Leblebici-Basar, D. and Altarriba, J. (2013), "The Role of Imagery and Emotion in the Translation of Concepts into Product Form", Vol. 16 No. 3, pp. 295–314.
- McNeill, T., Gero, J.S., Warren, J., Neill, T.M., Gero, J.S. and Warren, J. (1998), "Understanding conceptual electronic design using protocol analysis", *Research in Engineering Design*, Vol. 10 No. 3, pp. 129–140.
- Nagai, Y., Taura, T. and Mukai, F. (2009), "Concept blending and dissimilarity: factors for creative concept generation process", *Design Studies*, Elsevier Ltd, Vol. 30 No. 6, pp. 648–675.
- Pahl, G. (Gerhard) and Beitz, W. (1996), *Engineering Design : A Systematic Approach*, Springer.
- Pearson, D.G., Logie, R.H. and Gilhooly, K.J. (1999), "Verbal Representations and Spatial Manipulation During Mental Synthesis", *European Journal of Cognitive Psychology*, Vol. 11 No. 3, pp. 295–314.
- Purcell, a. T. and Gero, J.S. (1998), "Drawings and the design process", *Design Studies*, Vol. 19 No. 4, pp. 389–430.
- Reed, S.K. and Johnsen, J. a. (1975), "Detection of parts in patterns and images", *Memory & Cognition*, Vol. 3 No. 5, pp. 569–575.
- Roozenburg, N.F.M. and Cross, N.G. (1991), "Models of the design process: integrating across the disciplines", *Design Studies*, Vol. 12 No. 4, pp. 215–220.
- Sim, S.K. and Duffy, A.H.B. (2003), "Towards an ontology of generic engineering design activities", *Research in Engineering Design*, Vol. 14 No. 4, pp. 200–223.
- Verstijnen, I.M., van Leeuwen, C., Goldschmidt, G., Hamel, R. and Hennessey, J. (1998), "Sketching and creative discovery", *Design Studies*, Vol. 19 No. 4, pp. 519–546.
- Ward, T.B., Smith, S.M. and Vaid, J. (1997), *Creative Thought : An Investigation of Conceptual Structures and Processes*, American Psychological Association.
- Wilkenfeld, M.J. and Ward, T.B. (2001), "Similarity and emergence in conceptual combination", *Journal of Memory and Language*, Vol. 45 No. 1, pp. 21–38.
- Wisniewski, E.J. (1997), "When concepts combine.", *Psychonomic Bulletin & Review*, Vol. 4 No. 2, pp. 167–83.
- Wisniewski, E.J. and Middleton, E.L. (2002), "Of Bucket Bowls and Coffee Cup Bowls: Spatial Alignment in Conceptual Combination", *Journal of Memory and Language*, Vol. 46 No. 1, pp. 1–23.
- Wynn and Clarkson. (2005), "Models of designing", *Design Process Improvement*, Springer London, pp. 34–59.