Thinking difference: Theories and models of parametric design thinking

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The paper examines the uniqueness of seminal parametric design concepts, and their impact on models of parametric design thinking (PDT). The continuity and change within the evolution of design thinking is explored through review of key texts and theoretical concepts from early cognitive models up to current models of parametric design thinking. It is proposed that the seminal role for parametric schema, as a strategic medium of parametric design thinking, is formulated at the intersection of three bodies of knowledge: cognitive models of typological and topological design in architecture; process models of digital design; and tectonic order of material fabrication design (MFD). Differentiation is introduced as a key design strategy of PDT and is demonstrated through classification of prominent case studies.

Keywords: computational models, parametric design, design cognition, design knowledge, parametric design thinking

Beyond being another tool for modeling complex forms, parametric design is emerging as a unique and distinctive model of design. Both research and praxis in parametric design are influencing the emergence of parametric design theories that are currently undergoing a reformulation and an epistemological shift. In parallel, the development of current tools and practices of parametric design are beginning to impact forms of parametric design thinking (PDT). Current parametric design systems are adapting to changing context under the impact of a new generation of scripting languages and techniques (Burry, 2011), relational topological schema, associative geometries, and re-editing processes (Woodbury, 2010; Jabi, 2015) and computational process models of digital design (Oxman, 2006).

This theoretical review of *parametric design thinking* (PDT) is motivated by the need to explore the uniqueness of parametric design methods, techniques, media and tools within the field of design studies in order to understand the impact of parametric design on the emergence of new ways of thinking in design.

In parallel with the chronological development of media and tools in design, the theories and concepts of design thinking have evolved through both

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continuity and change in relation to accepted paradigms widely recognized scientifically as ways of design thinking. The first scientific foundation of design as a way of thinking appeared as a problem-solving paradigm in *The Sciences of the Artificial* (Simon, 1969). A body of ideas presented by Robert McKim in *Experiences in Visual Thinking* (McKim, 1972) focused on new visual aspects of design thinking. Ways of thinking in the discipline of architectural design were demonstrated by Bryan Lawson in *How Designers Think* (Lawson, 1980), and by Peter Rowe in *Design Thinking* (Rowe, 1987). These works presented theories and methods of design that were considered basic research in design studies. In the following years, design research has developed the relationships between design, cognition and computation, which have become an important topic in design studies (Oxman, 1994; Oxman & Gero, 1987; Oxman & Oxman, 1992).

Design thinking has been defined as a process of '*creative strategies which designers utilize during the process of designing*' (Visser, 2006); it has recently been proposed as '*a process of exploration and creative strategies*' in all design domains and has been recognized as a new field in other emerging design practices (Dorst, 2012). Following the evolution of cognitive and computational design research, the present study seeks to formulate the relationship between selected models of design thinking and the impact of currently emerging computational media. This is in order to characterize and evaluate the influence of novel digital design tools and technologies of parametric design in producing distinctive novel forms of thinking in design.

In order to formulate the uniqueness of parametric design thinking, a systematic theoretical study is presented below comparing selected cognitive concepts in both traditional paper-based models of design thinking and current computational models of parametric design. The systematic analysis and definition of a chronological process of evolution of models of design thinking is presented as part of the continuity and change in the evolution of models of design thinking (from cognitive models to computational models to models of parametric design thinking). Derived from this evolutionary framework of design thinking, the key concepts and principles of parametric design thinking are introduced, defined and illustrated. The process of tracing the transformation from traditional paper-based media to computational media-related models of design thinking has enabled the systematic identification of current seminal concepts and principles in parametric design thinking. The body of generic concepts that have been found to be associated with media-related strategies of design creativity in prominent models of design thinking have also provided new perspectives and understanding of thinking processes in design (Section 1).

As a result of the comparative study, unique cognitive concepts and principles in models of parametric design thinking such as: *Generic Schema; Relational*

Logic; and Associative Relationships; have been identified and framed in the current research as emerging models and methods of parametric design thinking. The research study has focused around the intersection of three research areas: parametric design models and tools, cognitive models of architectural design knowledge, and process models of digital design. The work has identified concepts and principles of generic schema in PDT in each of these areas of knowledge: the generic parametric schema (Section 2); the knowledge-based design parametric schema (Section 3); and the generic schema of information flow and process models of digital design (Section 4).

Finally, the concept of differentiation, as part of a current body of disciplinary knowledge in architectural design, is addressed within parametric design. The processes of thinking differentiation are presented and demonstrated by selected prominent architectural examples (Sections 6 and 7). Lastly, the uniqueness of PDT as a model of design thinking, its limitations and future potential, are presented and discussed in the concluding section.

1 Evolution of models of design thinking: from cognitive to computational to parametric design thinking

Due to the rapid development of the role of digital media in design practice, the study and understanding of the relationship between cognitive models and computational processes in design has gained important research priority in design studies (Oxman, 1995). In order to represent and understand the uniqueness of PDT a theoretical study comparing the evolution of models of design thinking was initiated. To conduct such a comparative study of different theories and models of design thinking it is necessary to select and define the cognitive activities that are among the most coherent and distinctive components which characterize the main activities in the disciplines of design.

Creativity has been recognized as one of the main cognitive activities in design studies that is addressed by almost all theories of design thinking (Boden, 1990; Cross, 1997). According to Dorst and Cross (2001) '*in every design project creativity can be found, if not in the apparent form of a distinct creative event, then as the evolution of a unique solution possessing some degree of creativity*'. Based upon this assumption, accepted cognitive concepts of creativity in different models of creative design were compared.

The main categories of creativity in design are shared by leading theories of design thinking. For example, the concept of exploration space in design was found as one of the main concepts appearing in all theories of design thinking. While the intrinsic concepts of creativity and innovation referred to in the semantic content of the term *designerly ways of knowing* (Cross, 1982, 2001, 2006, 2011) are shared by all design disciplines and across design scales, the strategies and methods for exploring alternatives in a solution space may be unique depending on the type of media technology.

The evolution of such key concepts has rapidly developed to adapt to the current emerging technology of computational media. Thus it can be generally observed historically that from hand-drawing and sketching, to code-based scripting in digital design, and up to the current prominence of parametric design thinking, emerging media and technology-related models of design have resulted in the rapid development and change of the concepts, content and procedures of design thinking.

The analytic objective of this review of theory has been to identify the evolution of design thinking from its origins to the current state of parametric design thinking. Selected representative theories and models of design thinking are presented and discussed in the following sections. Key cognitive concepts of design thinking are analyzed in each of the prominent models of design thinking. These include reference to a consistent set of concepts such as *search of solution space*, *exploration*, *emergence*, *reflection*, *modification*, *refinement*, *adaptation* and *media* including current computational design concepts such as *algorithmic design*, *scripting languages*, etc. This tracing of the evolution of the set of relevant concepts in the sequence of models demonstrates the impact of new technologies of computational media on the processes of parametric design thinking.

1.1 *Early models of design thinking* 'Designerly Ways of Knowing' *(Cross, 1982, 2001, 2006, 2011)*

These are among the early cognitive models of design thinking that appeared in the 1980's. Prominent among the large body of research in design thinking are observations related to personal introspective thinking in sketch-based media. Among the objectives of observational research methods of designer's behavior was to define how the designer works through the complex iterative cognitive processes of conceptualization, modification and refinement in a solution space. Reflection upon the result of a *design action* has from the beginning been a central concept in a *personal design process* where reflection means identifying the good results and the bad results of the sketch ideas at any time. Cross further identified sketch *modification* as part of a characteristic process of *refinement* of a design idea. The linked cycle of design, reflection, modification and re-design in an iterative process of successive *refinement cycles* of the design idea was the archetype of cognitive models of design thinking as a network of actions and reflection that exists as a significant stream of design research until today.

1.2 *Reflective practice as epistemological model* 'Reflection in Action' *(Schön, 1983, 1987, 1988)*

Schön's concept of reflection termed, *Reflection in Action* (Schön, 1983, 1987, 1988), was another important original foundational concept in cognitive approaches to design thinking. The systematized depiction of the iterative process through observation and visual documentation of the design process is usually accomplished through observation by protocol analysis. In this method the formalization and graphical documentation of the iterative cycles of design reflection are followed by framing the situation by the designer and evaluating a *design action move* for solution refinement as good or bad, and moving forward to the next action. For Schön the *move* is the action response to reflection. The process proceeds through further acts of *naming and framing* in which the design problem context imposes on the situation a coherence that guides subsequent moves. In Schön's formalization of design processes, *refinement*, or modification, is part of a *moving-seeing-moving* process. Design *refinement* through *a series of moves* is characterized as a kind of knowing process of *moving-seeing-moving* described variously as *fast moving … thinking on your feet* while recorded and supported by the medium of paper-based sketches (Cross, 2011).

A protocol of *patterns of reasoning* by designers using design rules can be derived from underlying types, references, spatial gestalts, and experiential archetypes that represent design knowledge or *holding environments* for reflection in action (Schön, 1988). Thus Schön's theories and research procedures included the establishment of important concepts and research methods for the future of design cognition research.

1.3 *Design thinking in early computer-aided design models* 'Architecture, Media and Knowledge' *(McCullough, Mitchell, and Purcell, 1990)*

With the gradual departure from paper-based design media since the 1980's until today there is a growing and profound series of changes in models of design thinking. The elements of this evolution occurred first as media technological developments. The evolution of computer-integrated design from one-off design modeling systems to designer supportive design environments and eventually to the truly generative geometric design machines (that parametric systems are rapidly becoming) has witnessed a substantive transition in the nature of design methods and processes. In the evolving relationship between man and machine the profile of the *designerly thinker*, including the required knowledge base, the skill set, the conceptual principles, and leading models of design have been totally transformed. Another contribution in defining this evolutionary process is the identification of the continuing role of the epistemological foundations of disciplinary knowledge such as typological knowledge in evolving models of design thinking (Oxman & Oxman, 1992).

Early CAD systems were generally a representational medium for the 2-dimensional and 3-dimensional modeling of designs that were sufficiently geometrically well-conceived and visualized so that they might be computationally modeled. Initially, within the limitations of Euclidian geometry, the CAD (or CAAD) modelers provided an interface for modifying views, enabling the possibility of walk-throughs, etc. Thus the ability to *explore* the one-off design was highly enhanced. Originally there existed no user interface to support a re-editing of reflection and processes of re-representation of computational 2D drafting and 3D modeling. With the technological and functional advances from CAAD to Parametric Design Systems we can observe the continuous mapping of early cognitive models of adaptation, or *re-modeling,* into current re-editing of code-structures and models in parametric systems which support contemporary *interactive parametric models of design thinking*.

1.4 *Artificial Intelligence and cognitive models* 'Knowledge-based Computational Models of Design' *(Oxman, 1994, 2004; Oxman & Gero, 1987; Oxman & Oxman, 1992)*

This period of far-reaching technological developments has raised challenging questions related to the impact of electronic media on new formulations of models of design process and design thinking. Early research and development on Artificial Intelligence (AI), and Knowledge-based Design (KBD), began to provide perspectives related to *cognitive structures, algorithmic systems* and *computational mechanisms* in design creativity and innovation. The cognitive depth of these models of AI in design was to later become absorbed into the development of advanced generations of computational design environments.

In early models of AI in design research, computational media associated with *knowledge-based design* were applied to formulate and represent design knowledge such as *experiential knowledge* and *precedent-based knowledge* (Oxman, 2004; Oxman & Gero, 1987). Models of cognitive processes of design thinking such as *refinement and adaptation* were developed through computational search mechanism of design. Knowledge types and sub-types related to *generic typological design knowledge* were computationally formulated by employing AI design media and tools (Oxman & Oxman, 1992). Such knowledge representation capabilities were later to be incorporated into parametric design systems (Oxman & Gu, 2015).

1.5 *Advanced computational design, algorithmic thinking and scripting* 'Scripting Cultures' *(Burry, 2011)*; 'Form + Code' *(Reas & McWilliams, 2010)*

The transition from traditional CAD to Computational Design to Theories of the Digital in Architecture, (Oxman, R.E, and Oxman, R.M., 2014) has contributed to contemporary models and methods of design thinking. Digital media and computational design systems have integrated processes of simulation, evaluation and fabrication within designer-authored scripted computational processes. Relevant principles from domains of science and philosophy, mathematics and computer science have introduced new ways of thinking and morphogenetic processes (Menges and Ahlquist, 2011; Oxman, 2015). This reformulation of objectives and scientific foundations has resulted in adding new principles, methods and processes to conventional cognitive models of design thinking.

The integration of materialization technology including 3D fabrication and robotics has advanced design to include both designing and making as integral components in models of computational design thinking. Tectonic relationships are informed by integrating design and materialization in the early phases of conceptual design. The selection of material and materialization techniques in early design stages is supported today by holistic process of information flow from concept to production. Furthermore, tectonic content such as structure and material is becoming part of a novel type of design thinking in what is currently termed, *Material-based Design* (Oxman, 2012). The traditional role of the visual strokes of the designer's pencil has now been replaced by the computer's algorithmic mode of thinking. *Algorithmic Thinking* can be defined as a set of rules written by a source code of explicit instructions that initiate computational procedures that generate digital forms. Writing algorithmic code has become a fundamental component of a *designerly way of knowing* in models of algorithmic design. *Scripting,* or writing code, provides a new way of design thinking. It demands the development of cognitive and computational skill for understanding the formalization, representation, and coding of design procedures. 'Software is a tool for the mind' (Reas & Fry, 2014). Scripting software programing languages allow the designer to adapt, customize and reconfigure the behavior of the software 'to fit his personal stylistic mode of thinking and working by scripting a dialogue' (Burry, 2011).

In the context of algorithmic design, being reflective relates to the designer's ability to understand and control the computational and scripting tools. 'Today, more than ever emphasis should be given to the intellectual foundation of this knowledge. Being a scripting digerati is simply not enough' (Oxman, N., in *Scripting Cultures,* Burry, 2011). Scripting languages have become part of all leading computational design software. For example, the *Processing* scripting language (Reas & Fry, 2014) enables visual designers and artists to adapt, customize and reconfigure the structure of the software to fit their personal stylistic mode of thinking. The scripting mode of creative thinking thus supports the exploration of solution space as part of a unique refinement search process. 'The designer is no longer making choices about single objects, but creating a matrix encompassing an entire population of possible designs' described as 'explorative reflection' (Reas & Fry, 2014;

Reas & McWilliams, 2010). Algorithmic code is thus related to the structure of the visual representation.

1.6 *Parametric design thinking* 'Generic Schema and Associative Relationships' *(Woodbury, 2010)*

Parametric design has currently emerged as an advanced form of design computational support environment. It contains a synthesis of many of the important design principles, concepts and methods that have appeared above. Parametric design as an act of design thinking is based on the exploration and re-editing process of associative relationships in a geometrical solution space.

The designer 'designs' the code of the *parametric schema* in order to design the design object. The *parametric schema* is a unique type of mathematical model that supports algorithmic processes of shape generation. Thus while there is continuity with the cognitive characteristics of exploration, generation, reflection and modification in traditional paper-based design, the logic and sequential components of the design process have been transformed. Furthermore, the built-in parametric variability of a knowledge-based cognitive schema in a specific domain provides a powerful new medium for design generation and innovation in all disciplines of design.

Parametric design has been defined as an exploration process of associative relationships of geometric concepts (Woodbury, 2010). Parametric tools enable reflection of both the associative logic and the geometry of the form generated by the parametric software. The design interface provides a visual screen to support visualization of the algorithmic structure of the parametric schema to support parametric modification. A re-editing process of the parametric schema becomes an act of skill in design thinking. After modification, the algorithmic software can complete a *re-editing process* of a parametric structure within the logic of the design schema.

2 Concepts and principles of the parametric schema in PDT

The motivation of this review of existing theory has been to explore the concepts and principles of parametric design and advance a new theoretical basis for understanding the current evolution of parametric design thinking.

The research study has focused around the intersection of three areas of knowledge: parametric design models and tools, cognitive models of architectural design knowledge, and process models of digital design. The work identified the following unique types of generic schema in each of these area: the algorithmic schema in parametric design; the cognitive schema of typological and topological knowledge in Architecture, and the computational schema of digital processes and information flow of evolutionary, performance-based and generative process models of design. The work explores the impact of these unique types of schema upon styles of design thinking from conception to production.

Parametric design thinking and the definition of its concepts and principles in design can be defined by the intersection of the three perspectives illustrated in Figure 1. The *parametric schema* is presented below, including concepts of algorithmic and scripting design models of PDT discussed in Section 2.1 and 2.2. Concepts of a knowledge-based cognitive schema in PDT are presented and discussed in Section 3 and the computational schema of digital processes and information flow in PDT is introduced and discussed in Section 4.

2.1 Concepts of algorithmic and scripting in PDT

Parametric design can be defined as a formation process of parametric structures of associative geometry that generates the geometry of desired objects of design. Terms and concepts such as *associative relations* and *topological geometry* are implemented in a parametric algorithmic schema.

The act of *scripting* is an essential component in formulating a *general theory* of PDT. In parametric schema the designer interacts with the parametric modeling system (such as Rhino/Grasshopper) employing visual coding symbols. The image of the design is then generated by the Rhino 3D modeling component of the system. The *parametric capability of the Grasshopper system* enables generation and modification of the design simply by changing parameters rather than the need to re-write substantial amounts of code. This is

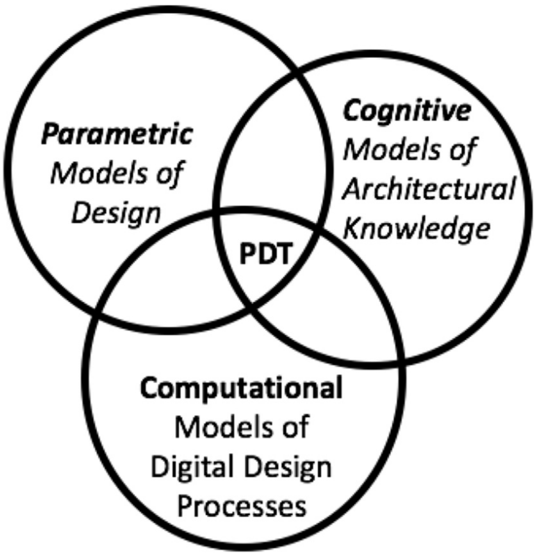


Figure 1 Diagram of intersecting fields of research in PDT

characteristic of a typical process of visual reasoning in which a parametric modification of the script maintains the main parametric relationships that have been initially defined. To summarize, the key-concepts and principles of parametric design in PDT are defined below:

- *Explorative mechanism of cognitive processes of refinement and adaptation represented by an algorithmic parametric schema:*

The formulation of algorithmic parametric schema is a fundamental cognitive capability of creativity of the computational designer. In the process of designing, the parametric schema can be modified and adapted. The cognitive role and the logic of a generic schema is proposed as a re-representation cognitive process of adaptation and refinement.

- *A versioning medium for exploring parametric variations of associative relationships and topological structures:*

The exploration power to produce variants within a parametric schema is a dominant characteristic of the parametric design process. The parametric schema supports form-generation strategies for exploring variations such as shape relations, structural organisation, scale and formal patterns.

- *Automatic algorithmic re-editing mechanism supporting models of re-representation:*

Current parametric design systems are replacing traditional CAAD remodeling with re-editing computational mechanisms to complete recognized thinking processes, providing a function similar to 'reflection in action'. Parametric tools, such as *Grasshopper*, also provide an exploration mechanism in which the history of the internal logic of all modification moves can be traced and reflected upon.

2.2 Concepts of visual representation in PDT

Traditional representations in design are focused upon the visual representation of the design object. Traditional visual representations are non-explicit with respect to *presenting the structural logic* that underlies processes of form generation and the logic of making the object under design. This logic becomes explicit in parametric design systems. In addition to this expanded visual content in parametric systems, additional specific design processes now exist including the integration of performance analysis and performative simulation with generative processes. Parametric systems can provide various types of informing processes including a visualization of both *code* and *form* of generative and performative processes of design.

The constructive logic becomes explicit by visual display of the separating parts of the schema (Davis, Burry, & Burry, 2011). In parametric design there are two types of visual display. A display of the 3D visual image is generated simultaneously to interactive programing by the visual scripting code. Parametric variations of the image can be updated and generated simultaneously in a visual display in parallel to the code modification.

The parametric schema supports topological variability that can be applied to both process and form. The parametric design process thus contains two parts: the design of the parametric schema for the design of desired solution and the interactive process of modification of the parameters of the schema in order to search through the family of sub-types designs. The solution space in modification and refinement is updated, simultaneously, on the scripting code and the visual display. As a result, the technology and the methods of parametric design have become a keystone of digital design thinking. Current software packages and parametric plug-ins are designed to provide such interactive interfaces.

Most cognitive theories of design refer to the cyclical and iterative model as the dominant model of design. In almost all known models such as *analysis-synthesis*, *generation-representation-evaluation,* and *reflection in action* the reflection phase is followed by re-representation of the visual representation of geometrical properties of the object itself. In order to operate in parametric design environments designers must adapt a different type of thinking. Design modification in traditional ways of thinking, is usually achieved by visual operations of re-drawing and/re-modeling of the object of design. While traditional models of design thinking refer to the element itself, in parametric design re-editing refers to design process represented by a set of algorithmic rules defined by the designer.

In parametric design the design object can be modified by an associative set of algorithmic rules. The designer can modify parametric values or change the relationships of the rules and let the system drive the whole process of visual re-representation modification of both algorithmic code and the 3D geometric model. Re-editing as a re-representation process is fundamentally different from the modification of traditional paper-based and 3D modeling of geometric representations. Furthermore, re-editing one parameter will generate a computationally modified structure of the associative rule set. This skill requires a different logic of thinking relative to algorithmic design thinking (Woodbury, 2010).

3 The cognitive model of design knowledge in the parametric schema in PDT

In traditional paper-based design in processes of schema-refinement and adaptation there is a *non-explicit modification process* of typological knowledge. This has been exemplified through a case study developed in prior research (Oxman, 1990, 1997; Oxman & Oxman, 1992). In traditional approaches of architectural and engineering design the design process is based on the modification and adaptation of typological knowledge (for example of dwelling types in architecture and type of bridges, or type of columns and beams in engineering).

In contrast, the definition of a parametric schema using typological rule structures is *an explicit act* in parametric design. It involves the knowledge of strategies and parametric methods of rule-based design. The knowledge of scripting is fundamental in re-editing processes of rule-modification in response to changing programmatic factors according to a modified programmatic context.

The cognitive logic of a generic parametric schema as a basis for exploration processes of solution space is by a process of parametric re-editing. Re-editing of a parametric schema (adaptation of parameters within the schema) can be considered an explicit process of re-representation. The unique cognitive logic of both, the typological parametric schema and the topological schema are a basis for exploration, creativity, and innovative processes.

3.1 Cognitive design schema of typological knowledge in PDT

A *Parametric Design Schema* of disciplinary typological knowledge is a computational form of the representation of generic domain knowledge in design. The cognitive role and the logic of a generic schema (referring in this case to the architectural knowledge of a classical temple typology), can be demonstrated through the example of the design of a Classical Greek Temple, reflecting the different plan styles, geometrical series and proportions (Oxman & Gu, 2015) (see Figure 2).

The roots of a *typological parametric schema* of the *Classical Greek Temple* can be considered as a rule-based representation of classical notation rules of *Greek Architecture* that were historically passed on without formal representation methods of design knowledge (Carpo, 2016). The Classical notation rules provide an example of the historical transmittance of a typological schema. Such verbal dissemination of *typological rules of proportions and combinations of elements* including procedural and geometric rules that can be understood as an early form of using a non-formal cognitive typological schema of design thinking. According to Carpo (2016) Deleuze observed and recognized the

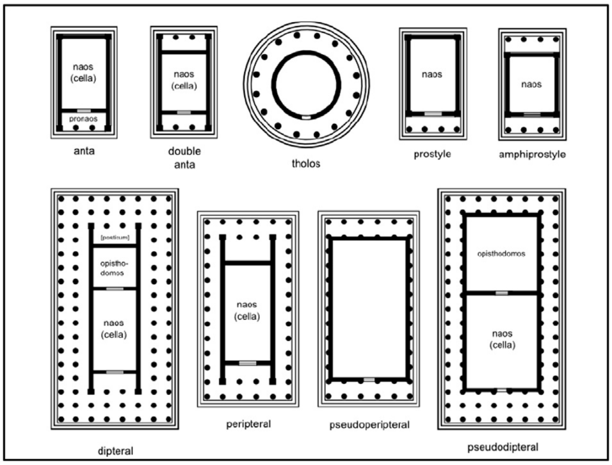


Figure 2 Classical variations of the generic order of the Greek Temple

generic power (of parametric notations) to describe and generate the whole set of typological variations of a *generic object*, later termed by him as the '*objectile*'. Today, this process of formulation of rule-based knowledge is similar to the definition of the parametric typological schema.

Two examples (see Figures 3a–c and 4) are used to illustrate the generic typological schema of *Classical Architecture*.

3.2 Cognitive design schema of topological knowledge in PDT

The cognitive logic of exploring variations in creative and innovative processes differs in typological and topological design. These two types of logic represent the distinction between a generic typological schema, referring to the explorative *design of sub-types* by changing of parametric variables, versus a topological-schema, referring to a topological explorative type of *design of versioning types* by changing the values of their associative relationships (Oxman & Gu, 2015).

The exploration process *of topological parametric design* relies on the generative power of the system to create an infinite range of topological versioning types that can be mediated by parametric modifications of associative relationships. In nature, topological form is maintained and transformed by environmental forces. Processes of growth and evolution of natural systems can be defined and traced by topological relationships. In natural environments, complex biological systems can grow and evolve by exchanging information with their environment. Natural principles of topology were employed by D'Arcy Thompson in his noted study of evolutionary processes in developmental biology (Thompson, 1917). His comparative analysis represents the

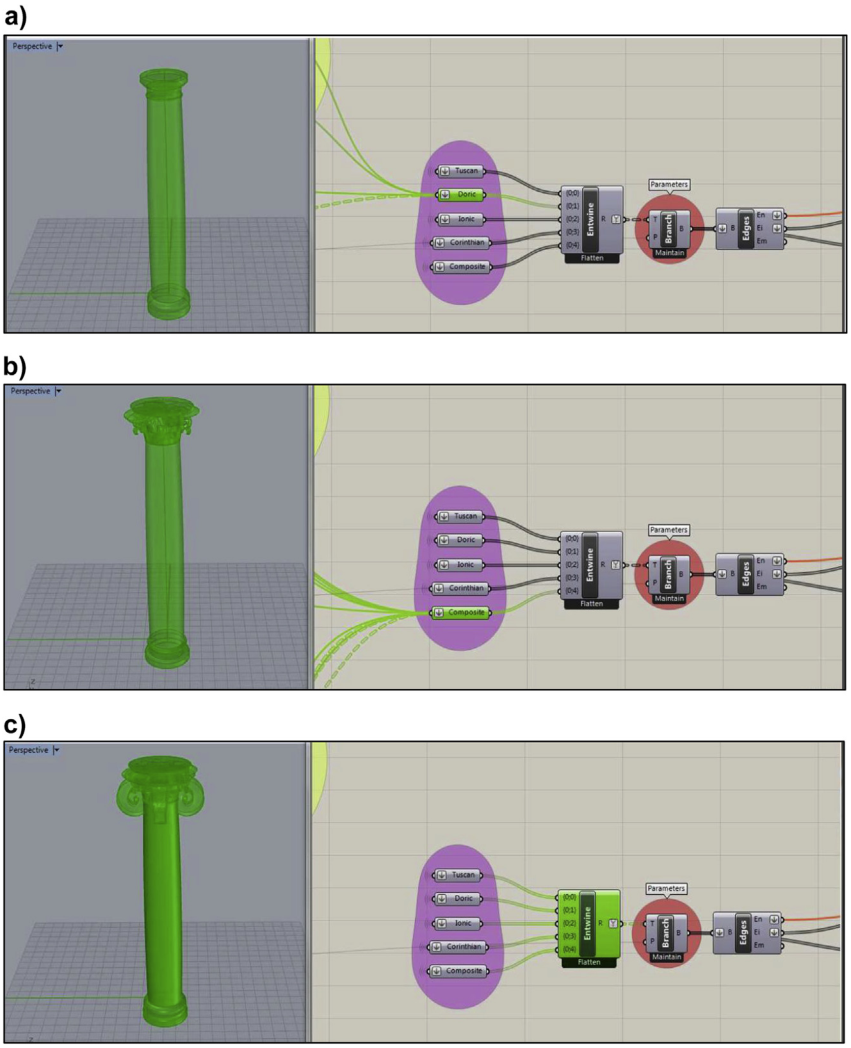


Figure 3 Exploration processes of typological rule-based knowledge: classical parametric variations of Greek columns (3a; 3b; 3c) 3D Rhino model*: left screen;* Grasshopper visual code*: right screen. Credit: Liz Leibovitch, Michael Weizmann, Anais Siman,* Digital Experimental Studio, *Technion*

topological relations between forms of sub-species that could be deformed into one another by topological transformations.

Typological thinking is argued by Jan Knippers as limiting the creative approach to exploration processes. Knippers (2013) argues that the creative style of thinking is replaced today by experimental design tested by materialization logic. This new *experimental logic* is supported by topological parametric design.

Figure 4 Topological curve design. Credit: Yarden Hadad, Inbal Tamir, Anat Saar, Digital Experimental Studio, *Technion*

In contrast to a varied typological schema of the classical column, a topological parametric schema is founded on *versioning moves* (Figures 4 and 5) that can be represented by rules of associative relationships and dependency. Understanding how to *manipulate and explore associative relationships and dependencies in topological geometry* are among the central concepts and principles of parametric design thinking.

The creative power of topological design is illustrated by the following two examples. The two design examples of a topological curve (Figure 4); and a three-dimensional wall illustrates the process of parametric design using *topological versioning strategies* to design and evaluate a three-dimensional, tripartite parametric wall of open mesh structure (Figure 5).

The exploration process of versioning strategies in different variations of the parametric wall design and the effect of the modulation of the central open wall zone upon the base and header zones has been developed and explored by re-editing the parametric schema; Figure 5a-top, illustrates a tri-partite mesh of a differentiated pattern; Figure 5b-middle illustrates a uniform mesh zone; Figure 5c-bottom illustrates a hybrid zone of a differentiated mesh pattern.

4 *Information flow processes in PDT*

In order to represent processes of parametric design there is a need to explicate the flow of information and the embedded logic in process models of

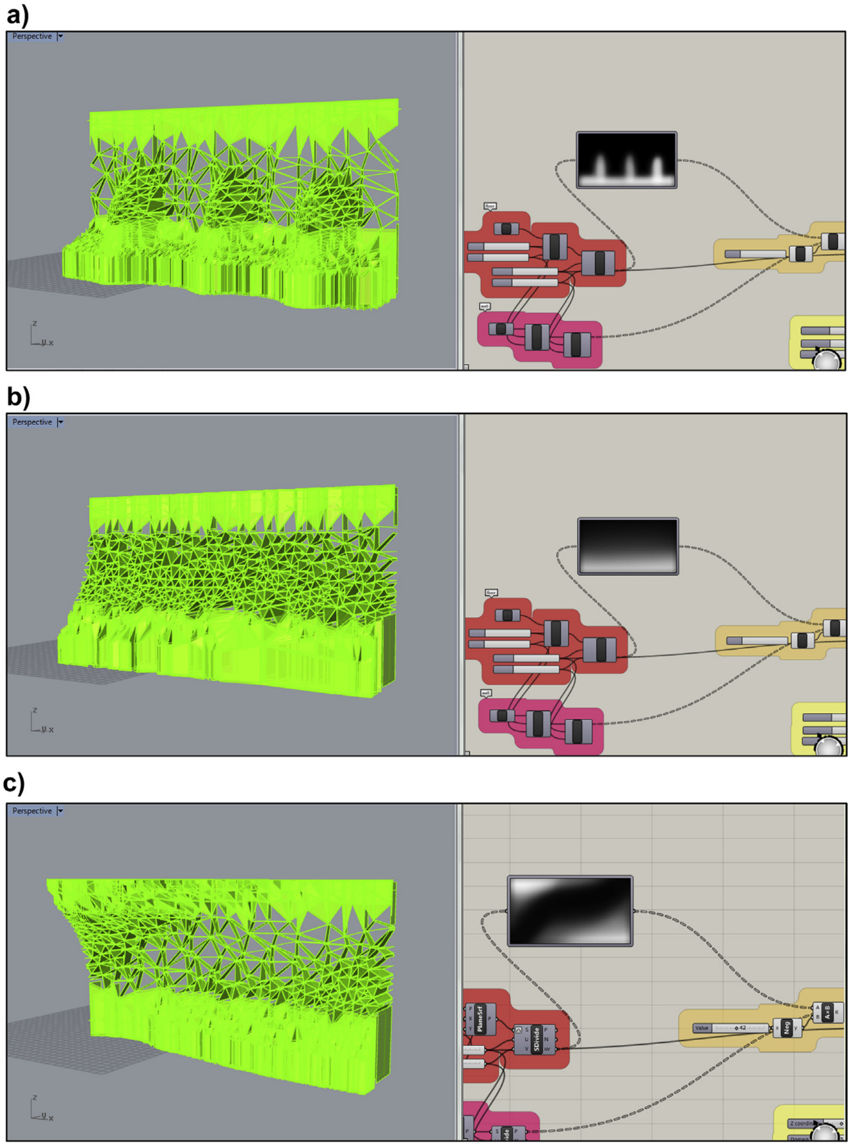


Figure 5 Exploring versioning strategies in a topological parametric wall design: (a) A tri-partite differentiation. (b) A uniform differentiation (c) A hybrid differentiation zone 3D Rhino model*: left screen;* Grasshopper visual code*: right screen. Credit: Liz Leibovitch, Michael Weizmann, Anais Siman,* Digital Experimental Studio*, Technion*

parametric design. This includes the explication of knowledge structures, the order of flow of information, and the parametric logic of design.

The process models and information flow diagrams (Figures 6 and 7) provide a generic formulation to represent the development of computational design processes over time (Oxman, 2006). The formulation is presented in the

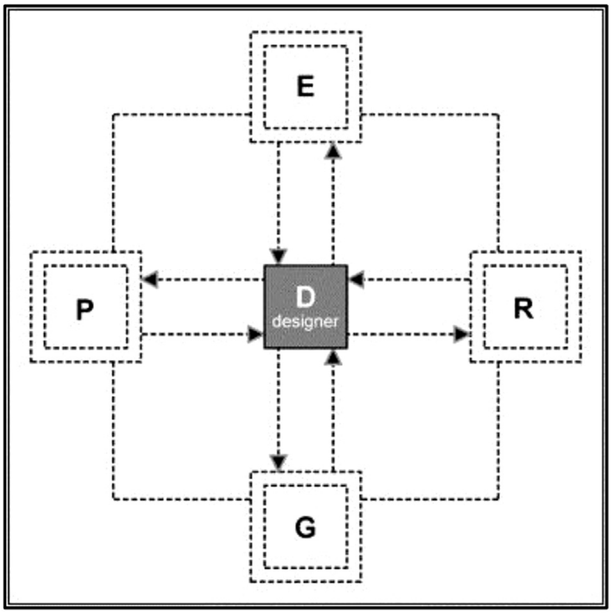


Figure 6 Generic schema of process models and information flow (2006) represented by links between Representation (R) Evaluation (E) Performance (P) Generation (G) R. Oxman, Design Studies (2006)

context of the current research in order to map diverse process models of parametric design.

The centrality of the designer in this schematic formulation (marked as D) implies that the traditional role of the designer as a *visual thinker* is maintained in parametric design (with respect to both code and form). Figure 6 (Oxman, 2006) includes the processes of a visual re-representation (marked as R), evaluation (marked as E), performance (marked as P), and generation (marked as G) in which both the non-implicit and/or the explicit-flow of digital information employ a central visual representation. Directions of the flow of information are represented by arrows. Additional symbolic designations provide for the notation of specific additional components of PDT processes.

The symbols in Figure 7 illustrate modes of interaction, links with visual representations, and types of interaction with digital media (in parametric design the diagram represented in Figure 7 employs the term digital media, refers to algorithmic languages, and scripting code). Their specific use in parametric design is explicated in the following diagrams (Figure 8) of various models.

4.1 Process models of information flow supported by parametric tools in PDT

Understanding and developing models of information flow in various process-based models of digital design (see Figure 8) are providing a foundation for

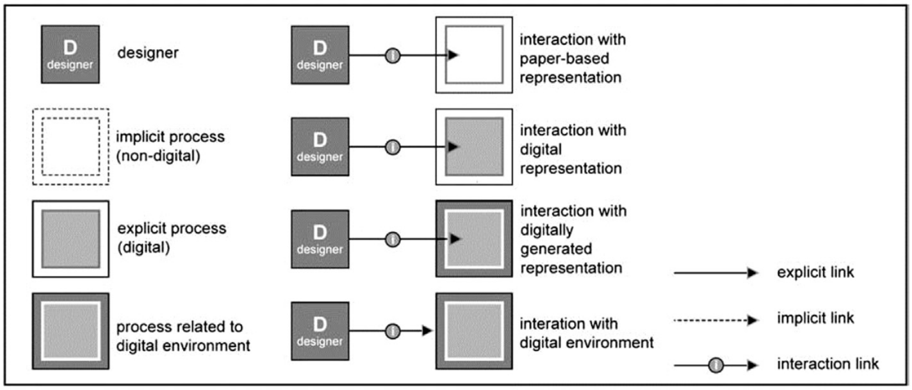
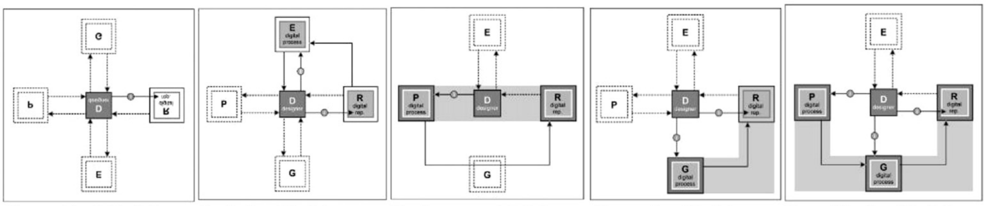


Figure 7 Graphical symbols of the generic schema. Credit: R. Oxman, International Journal of Design Studies*, 27 (3) pp. 229–265*



Geometrical Model *Evolution Model* *Performance Model* *Generative Model* *Form Finding Model*

Figure 8 Digital process models of information flow in digital design. Credit: R. Oxman, International Journal of Design Studies*, 27 (3) pp. 229–265*

understanding the current development of ‘plug-in’ parametric design tools which support digital process models of parametric of design thinking.

Design thinking in parametric design relies on tools that provide visualization of code and form of coded structure of the parametric schema and the 3D geometric model of the design object.

Models of performance-based form generation are currently supported by specific visual ‘plug-in’ tools in parametric design environments. Plug-ins such as *Kangaroo* (Form-finding with Computational Physics); *Karamba* (Structural Design); *ARCH-CFD* (Computational Fluid Dynamics); *Pachyderm* (Acoustical Simulation); Ladybug and Honeybee (Sustainable Environmental Design), etc. exist in order to provide analytical capability to support specific process models of PDT. In all plug-in tools of parametric design such as *Kangaroo, Karamba, Ladybug,* and *Honeybee*, the interactive display of the visual image is generated in parallel to an interactive programing window for modifying the visual scripting code. Furthermore, parametric variations of the image can be updated and generated simultaneously in the visual display in parallel to code modification in a re-editing process. Current software packages and parametric plug-ins are designed to assist processes of re-editing relationships replacing the traditional cognitive process of re-representation.

5 Material fabrication design (MFD) as a schema of disciplinary architectural knowledge in PDT

Today the convergence of design, engineering, and architectural technologies is breeding a new material practice in experimental design domains such as architecture. This shift is defined as a dynamic synthesis of principles of spatial, structural and material ordering that are integrated through materialization and fabrication technologies. Current discourse on materials includes concepts of materialization processes that are changing operative concepts of design tectonics in design thinking.

5.1 The integration of material fabrication in parametric design

Tectonics is becoming a seminal concept in parametric design due to current digital technology and computational informing processes that enable the mediation between *design and fabrication*. Tectonic relationships are being *informed* by holistic types of the logical flow of information from *conception to production*. This multi-stage process has been termed, *Informed Tectonics* (Oxman, 2012). The evolving processes of information have been defined by researchers in this field as a computational informing process that enhances the tectonic relationships between form, structure and material properties within the logic of fabrication and robotic technologies (Oxman, 2011).

One of the emerging aspects of materialization and fabrication processes has been the ability to alter the conventional order of tectonic processes in architecture from form-structure-material, to material-structure-form. This reversal of order has changed the traditional conceptual model of design thinking. In the traditional model of architecture, materialization follows conceptual design of form and the design of structure. Today, due to the growing importance of digital fabrication, the selection of materialization techniques can be an essential part of the *inception stage* in design. This development dictates an order of theoretical priority for material design in the conceptual thinking phase of design. Thus the new procedural order: *from material to structure to form* has relocated *material, materialization and material fabrication* to a level of priority in the PDT processes of architecture and other design disciplines.

5.2 Material fabrication design (MFD)

The current priority of materialization processes and fabrication technologies in architecture are breeding a new field of design research termed: *Material Fabrication Design* (MFD) (Oxman, 2012, 2016). By developing concepts, principles, and models of MFD designers are given the freedom to create new material-related experimental methods of design thinking that were previously considered difficult, or impossible, to implement (Figure 11).

As presented above, and in the following examples of leading architectural projects, MFD is defined today as a computational informing process that enhances tectonic relationships between form, structure and material within the logic of materialization and fabrication technologies. In computational informing process, information is translated directly into the control data that drives the materialization processes. The three key concepts of MFD are briefly described.

Material Design is defined as understanding and exploiting the properties and structural behavior of materials in the processes of design. Relationships with form, structure and construction are developed emphasizing the synthesis of complex orders in the design of elements such as building structures, building facades and envelopes.

Materiality is defined as digital tectonic content mediated by fabrication and robotic techniques. Categories of fabrication and materialization represent technological extensions based on both conventional and new materials and their relationships with form, structure and construction. *Digital Materiality* is considered as digital processes of materialization that contribute to new types of digital tectonics (Gramazio, Kohler & Oesterle, 2010; Oxman, 2010, 2012).

Fabrication technologies originally developed as media for *Rapid Prototyping* (RP). Today, the relationships between novel design technologies and techniques of fabrication are rapidly creating new ways of design thinking in

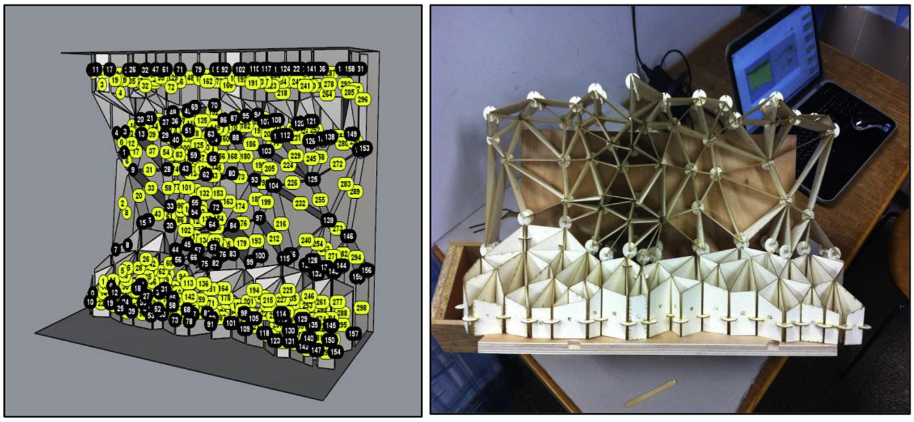


Figure 9 Parametric technique of assembly parts (Laser-cutting by Rhino Grasshoper). Credit: Liz Leibovitch, Michael Weizmann, Anais Siman, Digital Experimental Studio*, Technion*

Figure 10 Architectural parametric structure of MFD: Using scale of fabrication techniques as principles of a structural scale design. Credit: Metropol Parasol, *Seville, Spain Designed by Jürgen Mayer (2011). View of the parametric space grid structure. Source: Jürgen Mayer; Photos: Nikkol Rot Holcim*

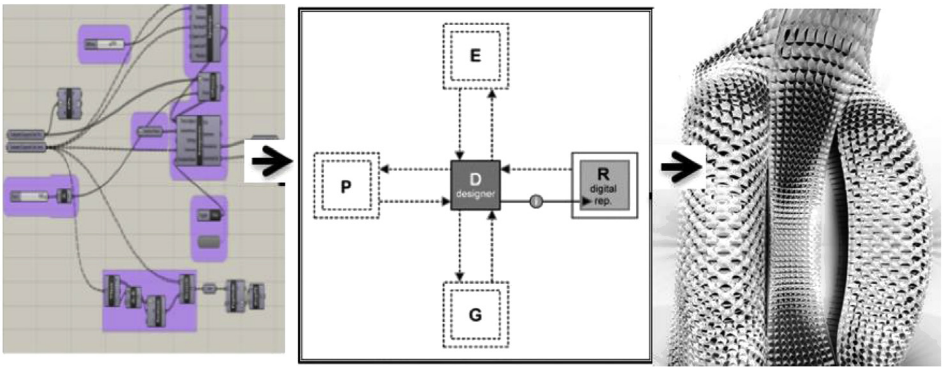


Figure 11 ***Formation Model (R)****. Experimental design of the parametric differentiation pattern for a high-rise building. Credit: Hadid-Schumacher Studio, the Angewandte Department of Architecture, Vienna (2007)*

design domains such as Architecture, Industrial Design, Engineering and other design disciplines. Designers are expanding the scope of design thinking by making design decisions related to the choice of technology and production method in response to new design complexities and innovative design. Fabrication processes are currently enabled within parametric software tools. The data for making assemblies of digital models for digital manufacturing are acquired directly from the parametric system (Figure 9).

In MFD processes, the formal and behavioral content of materials has become a dominant component of design conceptualization processes. The reversal of conventional information flow of tectonic order in design has given priority to materialization techniques of fabrication in thinking models of parametric design.

Principles of parametric fabrication techniques can affect the formal and behavioral content of material structures that become a dominant part of both the conceptualization stage and the materialization stage as in the *Metropol Parasol* in Seville (Figure 10) designed by Jürgen Mayer in 2011.

6 *Thinking differentiation in architectural design*

Relative to specific design objectives, parametric systems provide diversified explorative, context-based strategies of formal, generative and performative design in a parametric solution space. In contrast to traditional architectural composition processes, parametric design in architecture can be controlled by patterns of differentiation. Exploration, modification and refinement of code-based geometrical structures represented by a differentiation pattern, support various types of patterned processes of the object under design.

Differentiation in architecture may be considered as the *local specialization of a repetitive formation*. The objective of the specialization of a part of a regular system is to provide new types of formal, functional, performative, and structural properties and material behavior. From the point of view of novel modes of design thinking, the potential of using geometric patterns in PDT has had an impact on both style and model of design thinking. The functional and aesthetic power of differentiation is beginning to make a significant *parametric design thinking strategy* of current design in architecture.

In recent years, in a series of articles in professional journals, the term *Parametricism* has been proposed by Patrick Schumacher to indicate an architectural approach '*seen as a global type which draws its impetus from technological advancement and computational evolution*' (Schumacher, 2008). Helen Castle (Castle, 2016) has referred to these design characteristics as, 'a style that succeeds the modern movement'.

Schumacher has stated that: 'we pursue the parametric design paradigm all the way, penetrating into the corners of the discipline. Systematic adaptive variations, continuous differentiation (rather than mere variety), and dynamic parametric figuration concerns all design tasks from urbanism to the level of tectonic detail, interior furnishing and the world of products.' (Schumacher, 2008). In a recent volume of the British journal*, Architectural Design (AD),* entitled *Parametricism 2.0*, published and guest edited by Patrick Schumacher (Schumacher, 2016), a more realistic and less dogmatic view of parametric differentiation in architecture, urbanism and industrial design is proposed by Schumacher and other practice-based design researchers. Here, the potential of *Parametricism* is considered to help solve environmental problems and social issues through formal and functional solutions derived from exploiting pattern mechanisms of parametric differentiation. As such, *Parametricism* can be described both as a parametric design thinking strategy as well as a process-driven model of parametric design thinking (PDT).

In the following sections, the potential of parametric differentiation is proposed and exemplified as a computational model of parametric design thinking.

6.1 Process models of differentiation in parametric design

Differentiation is a term in the field of calculus, and continuous differentiation can be considered as the 'geometrical transcoding of parametric variations into differential geometries driven by iterative versioning processes of parametric design in a continuous rhythm' (Jabi, 2013). The exploitation of differentiation as a design strategy in parametric systems is unique as a design medium that can support a versioning series within otherwise continuous fields. This strategy can be applied in both parametric design and fabrication. Within processes such as form-finding, performance-based and generative design, differentiation patterns provide a medium for versions of exploration moves that are interactively initiated by the designer. That is, within each parametric version of the schema the designer can interactively modify the rhythm of geometric structures as seen in the example in Figure 5a–c above.

In each one of the following diagrams the role of a dual visual interface supporting code input and resultant 3D visual representation, is presented and illustrated. Each of the illustrative diagrams presented below represents the three components of information flow process in parametric design: the first, presents (by the same visual image) a symbolic differentiation code (left side); the second presents a unique process model of information flow (middle) and the third represents a selected image of a 3D model in the field of architecture (right side). In each of the three characteristic parametric design processes, the information flow diagram (center) differs (Figures 11–13).

The diagram in Figure 12 presents an evaluation process model of the design of a cylindrical structure employing FEA Finite Element Analysis software (load forces are displayed in color). Optimizing the relationship between form and structure is achieved by exploring the particular form of structural differentiation within the geometrical pattern of the design.

In parametric generative processes the 3D model is generated in reference to the input of a visual scripting code. Parametric differentiations of the tree

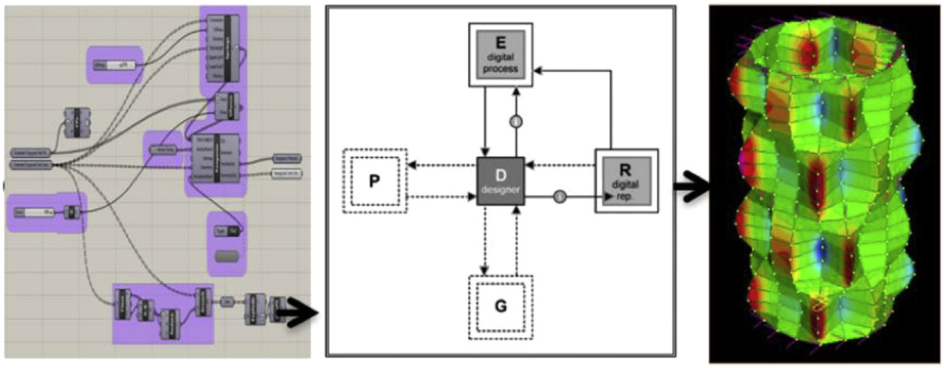


Figure 12 ***Evaluation Model (E)****. Representation and parametric differentiation of structural properties in design. Credit: N. Oxman*

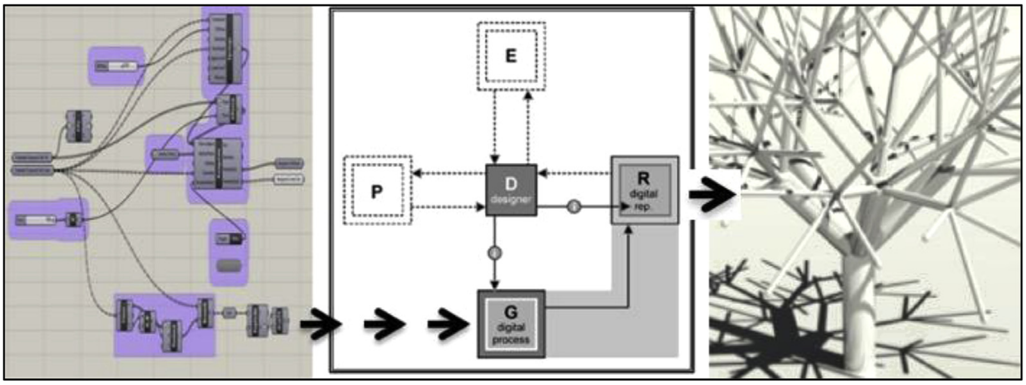


Figure 13 ***Generation Model (G)****. Parametric recursive differentiated branching as a design medium of generative design. Credit: Mor Herman,* Digital Experimental Studio, *Technion*

structure presented below can be modified and generated simultaneously to code modification of selected differentiation patterns (Figure 13). The diagram illustrates the visual interface for interactive code input and the resultant 3D representation of the geometrical model.

The design of a dynamic model of performance-based design requires representation of temporal dynamic solar properties. By using a pattern of parametric differentiation the dynamic behavior of the louver system can be represented (Figure 14). In all dynamic and responsive systems, the potential for differentiation provides a design medium for the simulation and exploration of performance/time responsive systems.

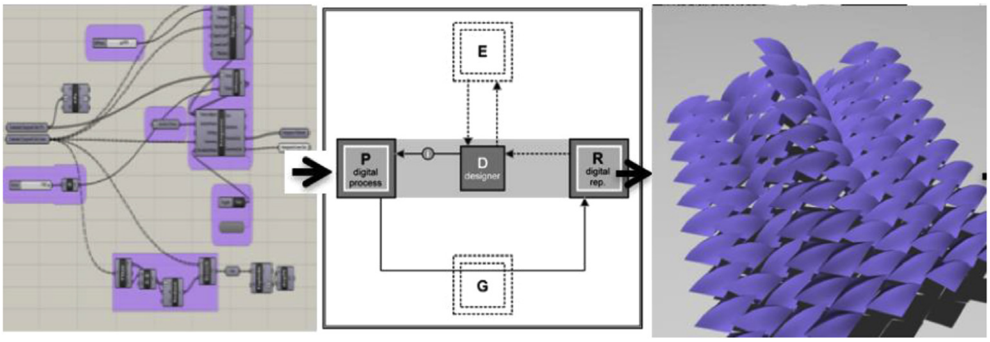


*Figure 14 **Performance Model (P)** in the design of a dynamic system of louvers. Credit: Shoham Ben Ari,* Digital Experimental Studio*, Technion*

7 Thinking difference: classes of architectural types and forms of differentiation patterns in PDT

Differentiation gradient thinking within the topology of a parametric pattern has become a significant medium of design in current architectural design. Differentiation in parametric design can be treated as a feature of a versioning process that allows for difference to occur within a continuous field, or rhythm (Jabi, 2010). In contrast to parametric instances in typological parametric schema, differentiation can be defined as a type of *topological parametric versioning schema* that differentiates a formal topological pattern of the design in response to functional and contextual environmental goals and constraints.

As has been defined above, differentiation patterning in architectural design is a unique strategy of PDT. In order to understand the application and purposes of *parametric differentiation patterns* we have defined types of differentiation as a medium of designing in architecture.

The following brief study presents an approach to the definition and classification of specific differentiation approaches in specific contexts, goals and constraints in architectural design. The study is presented below through the illustration and classification of a series of types of differentiation in architecture. The following case studies represent a topological basis for the selection of the specific differentiation pattern. Topological relationship of form, structure, tectonic model, and types of materialization (MFD) enabled both design and materialization of complex forms by designing a specific differentiation pattern as a medium of architectural design. In addition to functional objectives, each of the architectural projects presents forms of stylistic distinctiveness and performative behavior. In each one of the represented case studies unique architectural differentiation patterns are presented by the intersection of the following categories:

- Process Model of Digital Design
- Architectural Model of Tectonic Order (MFD)
- Differentiation Pattern
- Architectural Design Medium

The next sections present the architectural design strategy of differentiation design in selected architectural case studies, each of which may be considered as a novel strategy of design thinking in PDT.

7.1 *Differentiation of a gradient geometric pattern – as a modifier medium of diverse functionalities*

Case Study: *The Broad Museum; Los Angeles, 2015; Diller Scofidio and Renfro*

- **Process Model of Digital Design**: Geometrical Formation Model
- **Architectural Model of Tectonic Order**: Form-Structure-Material
- **Differentiation Pattern**: Gradient mesh of rhomboidal surface
- **Architectural Design Medium**: Modifier medium of diverse functionalities

In the recently constructed Broad Museum in California (Figure 15) the interior gallery space of the museum is provided with a continuous solar control and modulation system. In the case of this building, this is a fixed system. Termed the 'Veil' by the architects, this continuous parametric rhomboidal surface pattern covers the exterior wall and the roof of the museum. The mesh continuity is differentiated in geometry for lighting control of the

Figure 15 Differentiation of geometric pattern as a modifier medium of diverse architectural functionalities: The Broad Museum Los Angeles 2015, Visualization of Main Entry Facade. Credit: Broad Art Museum; Diller Scofidio and Renfro

skylights of the roof. Furthermore, the function of the wall surfaces is locally modified for architectural purposes such as opening up of the entrance area and in order to provide exterior exposure of the glass wall and public areas of the building. A large sculptural indentation on the second floor of the façade further modulates light at the pedestrian arrival point to the exhibition levels of the building.

7.2 Differentiation of a structural mesh as a medium - of an ecological responsive skin

Case Study: *Louis Vuitton Store, Macau, 2007; Zaha Hadid Architects*

- **Process Model of Digital Design**: *Performance-based Ecological model*
- **Architectural Model of Tectonic Order**: *Structure-Material-Form*
- **Differentiation Pattern**: *Gradient packing of circular elements*
- **Architectural Design Medium**: *Structural mesh medium of responsive skin*

The experimental design for the Louis Vuitton Store in Macau (Figure 16) from 2007 presents certain additional characteristics of differentiation in PDT. As with the case of the Broad Museum, the Zaha Hadid design for the Louis Vuitton store is a protective mesh structure for the external skin of the building. The typological structure in this case is a mesh structure of circular packing of a gradient system of elements.

The functional behavior in this experimental project was intended to provide an *ecologically responsive differential pattern*. Within the structural thick wall of the evolutionary elements it is possible to modulate and control direct solar penetration, as well as the to control viewpoint and to provide for the

Figure 16 Differentiation of a structural mesh as a medium of an ecologically responsive facade Louis Vuitton Store, Macau, Zaha Hadid Architects 2007. Credit: Zaha Hadid Architects

introduction of other elements such as signage, external lighting, etc. In this experimental design, the wall structure has become the structural support of the roof element. Thus, the skin is both performative as well as an ecological responsive design system in the PDT of this project.

7.3 *Differentiation of expanded aluminum metal screen – as a medium of modulation*

Case Study: *Messe Basel New Hall, 2013; Herzog de Meuron*

- **Process Model of Digital Design**: *Material Formation Model (MFD)*
- **Architectural Model of Tectonic Order**: *Material-Structure-Form*
- **Differentiation Pattern**: *Expanded metal aluminum mesh*
- **Architectural Design Medium**: *Modulation medium for program and function*

In the design and construction of the New Hall of the Bern Messe of 2013, by the Swiss architects, Herzog de Meuron (Figure 17), an expanded metal aluminum mesh screen provides a similar function for the two upper levels of exhibition halls within this building. The building, the function of which is to provide three new independent halls for the Bern Messe, is treated as three superimposed buildings. The metal mesh screen is differentiated in form by bending and folding the structure of the screen in a process similar to the 'expanded metal' well known in building. This much larger mesh is a skin that can be treated as a gradient surface and can be differentially modulated, thus providing a distinguishing architectural form and view possibilities for each of the three halls.

Figure 17 Differentiation of a metal mesh screen as a medium of distinguishing programmatic functions Messe Basel New Hall, Herzog de Meuron 2013. Credit: Herzog de Meuron

7.4 *Differentiation as medium of experimental structural design*

Case Study: *Venice Architecture – Biennale, 2016; Philippe Block (BRG at ETH, Zurich)*

- **Process Model of Digital Design:** Performance based structural design model
- **Architectural Model of Tectonic Order:** Material-Structure-Form
- **Differentiation Pattern:** Differentiation of form in bending
- **Architectural Design Medium:** Medium of structural form finding optimization

The BRG Block Research Group led by Philippe Block at the ETH Zurich has become noted for its experimental structural design using parametric design as a basis for a new approach to design that transcends the typologic and calculation approaches of structural building types. His approach exploits parametric structural form finding through digital parametric processes and performance models of structural design. Parametric models constructed by algorithmic scripts can generate designs by changing geometrically associated parameters according to given structural forces and properties of materials of design in different contextual conditions. This is accomplished both through digital simulation and the physical experimentation of experimental models. This follows upon much pioneering work of proto-parametric structural designers such as Gaudi, Frei Otto, and, in the case of the study below, the shell structures of Felix Candela and Heinz Isler (Block, 2016).

This exhibition at the Venice Biennale of 2016 (Figure 18) illustrates an example of contemporary experimental vault structure replacing the traditional masonry materials and the traditional methods of ribbed vaults with new material fabrication methods and techniques. The project demonstrates how new structural generative processes of form finding and optimization methods can generate geometry of compressive vaults that are absorbed by tension ties. Following historical precedents, these vaults demonstrate a new approach to PDT in vault design and construction that saves constructional weight and environmental impact and can be created by 3D print technology.

7.5 *Differentiation as medium of multi-functional performative design*

Case Study: *Chaise Lounge, 2008–2010; Neri Oxman (Mediated Matter Group at MIT) in Collaboration with Craig Carter 2009*

- **Process Model of Digital Design**: *Performance based generation*
- **Architectural Model of Tectonic Order:** *Digital Material-Structure-Form*

Figure 18 Differentiation as medium of experimental structural optimization Beyond Bending – *Venice architecture Biennale 2016; Philippe Block, BRG ETH Zurich. Credit: BRG at ETH/Iwan Baan*

- **Differentiation Pattern**: *Voronoi Differentiation*
- **Architectural Design Medium**: *Medium of 'multi-functional performative design' of Variable Properties Design (VPD) of structural surface pattern*

Neri Oxman at MIT and her research group (Mediated Matter/Media Lab) are inspired by nature where form-generation is driven by growth processes, topological versioning and variable properties of material in the behavior of natural systems. The term *Material Ecology* coined by Neri Oxman seeks the integration of form, material and structure by incorporating algorithmic form-finding strategies (Oxman N., 2011), and the invention of fabrication techniques of 3D fabrication technologies.

Figure 19 Medium of 'Multi-Functional Performative Design' of Variable Properties Design (VPD) of structural surface pattern and digital materiality Chaise Lounge, Beast, *2010; Neri Oxman (Mediated Matter Group, Media-Lab, MIT) in collaboration with W. Craig Carter (Material Sciences MIT). Credit: Production: Stratasys 3D printed with Stratasys multi-material 3D printing technology; Photo credit: Neri Oxman*

The design of the chaise, *Beast* (Figure 19), is an example of replacement of traditional information flow from *Form-Structure-Material* to *Material-Structure-Form* that incorporates a novel fabrication technology termed, '*Variable Properties Design (VPD)*. *VPD* is considered to be a design model, a methodology and technical framework by which to model, simulate, and fabricate material assembly with varying parametric properties designed to correspond to multiple and continuously varied functional constraints' (Oxman, 2008). This approach can be regarded as a unique computational model of PDT. This unique thinking process in which the invention of a novel tool, technology or technique reflects and guides the creation of the object itself can be regarded as a novel model of PDT (see Figure 19).

In the design for the chaise lounge (Beast, 2010) differentiation is achieved by the differentiation of Voronoi tiling of a parametric surface that provides a *multi-functional performative design approach* to the structural surface pattern of the chaise; this is accomplished through *Variable Properties Design* (VPD). That is, the 3-d printing process is guided by performance-based differentiated properties of a digital material. This is illustrated by the design of the continuous skeletal area of the shell structure (black), the support structure (grey) and comfort and softness supports (white) at the areas of bodily pressure.

7.6 Differentiation as a design medium of structural sectioning - materialized by fabrication techniques

Case Study: *Metrapol Parasol Seville, Spain (2011); Jürgen Mayer–Hermann and Arup Engineering*

- **Process Model of Digital Design**: *Performance-based Model*
- **Architectural Model of Tectonic Order**: *Form-Fabrication-Structural Material*
- **Differentiation Pattern**: *Force Form Differentiation*
- **Architectural Design Medium**: *Medium of structural sectioning, materialized by a form-force pattern and a parametric fabrication technique*

Figure 20 Urban plaza, Metropol Parasol, *Seville, Spain. Jürgen Mayer–Hermann and Arup Engineering (2011). Credit: Jürgen Mayer–Hermann and Nikkol Rot for Holcim*

Metrapol Parasol designed by Jürgen Mayer—Hermann and Arup Engineering (Figure 20) is the name of a partially covered, multi-functional urban plaza in Seville, Spain. The design of Jürgen Mayer and Arup Associates essentially provides three vertical zones of function: an elevated plaza; a ground level of archeological findings; and the visually dominant major element of an elevated wooden grid structure — the *parasol* — that is both an urban-scale shading element as well as an elaborated viewing platform raised on six large *mushroom columns*, or vertical structures.

The cloud-like form of the parasol structural network has been influenced by the structural forces, programmatic requirements, and environmental conditions. The material of the structural system was formulated after the selection of the fabrication technique. Finally, the form and the dimensions of the structural sectioning were informed by structural force properties represented by a differentiation structural model of a force-field pattern.

The urban-scale parasol is designed as a wooden grid-lattice structure implemented by parametric fabrication technique to create an organically flowing form in response to structural loading. *The diversity of the structural sectioning was designed by a Force-Form differentiation pattern*. The negotiated process between form and structural forces is reminiscent of Gaudi's use of catenary experiments in the structural design of the Sagrada Famila church in Barcelona.

To summarize, differentiation patterns of PDT as a design strategy in architectural and urban scale are, as yet, little studied or developed in architectural thinking. Such PDT applications in both scales are a future field for research in design.

8 Summary and conclusions: contributions to research and praxis of PDT

Beyond being another tool for modeling complex forms, parametric design was presented in this research paper as a unique and distinctive model of creativity and innovation in parametric design thinking (PDT).

The systematic theoretical analysis and definition of the chronological evolution of models of design thinking from the origins of cognitive models and up to PDT demonstrated both the *continuity and change in the evolution of models of design thinking*. The presentation of the transformational evolution process of thinking models in design; from traditional paper-based media to computational media-related models of design thinking has identified seminal shared cognitive concepts during a substantive change to media-related methods, principles and techniques in PDT.

The research study presented above explored knowledge of three intersecting fields of knowledge: parametric design models and tools; cognitive and computational models of architectural knowledge; and process models of digital design. Unique types of *generic schema* in each of these areas: the *algorithmic schema* in parametric design; the *cognitive schema* of typological and topological knowledge in architecture, and the *computational schema* of digital processes and information were defined and illustrated. Contemporary process models such as formation, evolution, performance-based; and generative process models of design have been demonstrated as holistic processes of design thinking *from conception to production*.

Parametric design has been presented as *a new paradigm of design thinking*. The evolution of leading concepts of design thinking from *typological thinking* to *topological design thinking* in creative design is one of the most distinctive changes in design thinking in the design disciplines. The centrality of *topological variants in design* and *topological versioning in the design medium of the parametric schema* has been demonstrated as a seminal theoretical and operative methodological concept in PDT.

Understanding and learning a new *symbolic role of imagery* in design is among the foundations of PDT. *Sketching by code* is not only a possibility, but promises to become *a new norm of skill and knowledge*. The traditional role of the visual image in paper-based design is replaced by both *the integration of visual form and visual code* in parametric design. The relationships between the visual image of design form and visual scripting code in parametric tools have been demonstrated by, and illustrated in, diagrams. This relationship is supported by a *visual interface* for *cyclical exploratory re-editing and interpretation processes* in PDT models of architectural design. Thus PDT is an *evolutionary process of explorative design of the parametric schema*.

Integrating PDT and MFD as a new class of disciplinary knowledge is challenging the culture of design in all fields of the design discipline. Disciplinary knowledge of novel types of material design, and fabrication and materialization technologies (MFD) in parametric design represent a unique form of tectonic thinking in current PDT. *Materiality* relates to tectonic design mediated by fabrication and robotic techniques. *Digital Materiality* is considered as digital processes of materialization that contributes to new types of digital tectonics such as with advanced 3D printing technologies. Understanding the evolution and change of concepts of MFD contributes to novel processes in design thinking models in parametric design.

Leading concepts of *topological design thinking* offer unique design methodological approaches in PDT. Mediated by recent parametric design tools, parametric design can be seen as a new operative model of design thinking. While the traditional typological mode of thinking (of generic types of forms and functions in disciplines such as architecture and structural design) may limit creative processes of exploration, differentiation strategies in a topological mode of thinking supports new types of creative thinking in innovated design. Understanding how to manipulate and explore associative relationships in topological parametric schema is emerging as both of a model and a style of design in PDT.

Differentiation patterns are an *ensemble collection* of the intersection of prior models. The ensemble of prior models now includes the *process models of digital design and information flow*; the *disciplinary models of tectonic order, materialization in MFD models,* and the selection and implementation of *differentiation patterns*. For disciplines such as architecture there is now a challenge to develop and formulate new disciplinary knowledge (such as new types of differentiation patterns) in the transitioning to a normative production of knowledge in parametric design.

Parametricism as formulated by Schumacher as a new style, is in fact both, a new style and model of design. It represents both a new body of knowledge and new methodologies in the design disciplines. PDT should exist as a shared design paradigm among all specific domains (e.g. architectural, structural engineering, and materialization) producing holistic conceptual thinking processes from conception to fabrication. This is a new horizon of theory and pedagogy for the future of design thinking.

The tools and practices of parametric design are beginning to impact new forms of development in the institutions of education and practice of design culture. Scripting and tool-making are becoming required forms of knowledge in research, education and practice. Is this to become core knowledge of design in academia and practice?

Finally, parametric design has been presented as a new paradigm of design thinking that integrates and advances certain of the concepts of prior models of design thinking. Design research in this area should become more strategic, computationally informed, and performance-based; it should be oriented to the production of knowledge relative to specific programmatic and functional requirements given by specific contexts. It is the integration of generic knowledge such as types of generic parametric schema with new forms of disciplinary knowledge such as MFD that is creating new forms of disciplinary knowledge in design.

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