Theory and design in the first digital age

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Digital design and its growing impact on design and production practices have resulted in the need for a re-examination of current design theories and methodologies in order to explain and guide future research and development. The present research postulates the requirements for a conceptual framework and theoretical basis of digital design; reviews the recent theoretical and historical background; and defines a generic schema of design characteristics through which the paradigmatic classes of digital design are formulated. The implication of this research for the formulation of 'digital design thinking' is presented and discussed.

Keywords: digital design, design theory, design methodology, design thinking

The evolution of digital design as a unique field of design endeavor, motivated by its own body of theoretical sources, promulgated by a culture of discourse, supported by new technologies, and producing unique classes of designs is a phenomenon that has been rapidly crystallizing in the past decade. Among the significances of digital design for the design theoretical community is the way that this form of highly mediated design is beginning to evolve unique design methodologies, unique forms of design interaction and unique formal content. Due to the large body of diverse publication that has accompanied these developments the problem of encompassing the intellectual domain of digital design culture is, in itself, a difficult mandate. Beyond this problem of diversity, there are other, more theoretical, challenges to our interpretation and understanding of digital design.

A high level of publication on the subject has been buoyed by the intensity of interest of the design professions in the new design possibilities as represented by dramatic form-generative potential. In architecture, product design and other design fields, this imagistic innovation, quickly recognized by younger experimental design practices, has been a driving

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force in the promulgation of a digital design culture. It is against the background of this highly active recent period of design development and the various attempts to theorize these events that encourage means of defining and mapping these phenomena.

Given the growing amplitude of issues and subjects in digital design as witnessed by both practice and publication, we are faced with the need to formulate a theoretical framework that is suitable to the conceptualization of the subject. Such a framework must be capable of contributing a relevant theoretical structure to the field, whereas its own theoretical disciplinary contents must also illuminate seminal issues. This research is intended to begin to address these challenges.

Among the characteristics of publications in the field as described in the following section is their emphasis upon the documentation, explanation and interpretation of design objects and their rationale. This appears to be a critical missing link, if we are to be able to address the central questions and future possibilities of digital design. One of these central questions relates to whether, in fact, digital design is a unique phenomenon – a new form of design – rather than merely a conventional design accomplished with new media. If this radical assumption is valid, then a comprehensive theoretical formulation of digital design might also contribute to new interpretations of certain of the root concepts of our extant design theories. Among these concepts challenged by digital design processes and therefore requiring the reconsideration of their formulation in design theory are fundamental ideas relevant to design thinking and concepts related to design methodology such as representation, generation, and interaction.

Beyond this implicit need to formulate a general framework for digital design there appears to be a current priority on establishing theoretical agenda that is relevant to design research as well as to theory and praxis. Digital design and its growing impact on design and production practices are suggesting a need for a re-examination of theories and methodologies in order to explain and guide future research and development. Prior research in design methodology and design thinking has frequently been centered on the analysis and formal modeling of behavioral, procedural and the cognitive activities of designing (Cross, 1984, 2000; Mitchell, 1990; Lawson, 1997). Certain of these leading studies may now provide a sound basis for identifying, comparing and transfiguring the differences between conventional paper-based design and mediated design environments. We propose that a new theoretical framework for formulating the characteristics and

theoretical issues of digital design can, in fact, be formulated in reference to certain of the extant canonic models of design. It is the intention of this research approach to attempt to achieve a definition and theoretical formulation of digital design in this way. Therefore, we propose to proceed to unknown intellectual territory by passing over certain well-known design theoretical ground.

First, a brief introduction to the set of phenomena that characterize the emergence of a digital design discourse is presented. This includes a review of significant events and precedents that are associated with the emergence of new digital paradigms. Following this general introduction and literature survey of the field, the problems of the scientific definition and theoretical formulation of key and characteristic aspects of digital design are addressed. This conceptual formulation through the identification of relevant early models of design including a discussion and presentation of their logic, structure and morphology is proposed as a basis for analysis and re-examination. On the basis of this analysis of extant models, a general representational schema for the presentation of various models of digital design is developed.

This general schema provides a framework within which to foreground the various components, processes, and issues that differentiate it from conventional paper-based design. The impact of digital techniques on the emergence of processes related to basic components of design such as presentation, generation, performance and evaluation are identified. Essential changes and modifications in traditional design models are defined and explicated, and new models are proposed. Through this process of the examination and modification of current models, a series of novel models of digital design are proposed.

The result of this theoretical and analytical research has been the formulation of both a schematic conceptual framework of digital design as well as a proposed series of paradigmatic models. In the final part of this research, this body of work then functions as an illuminating basis for the presentation of other aspects of digital design beyond models and methodological characteristics. Among these are future implications for new and complex relationships between designer users, digital design toolmakers, and design media. Furthermore, related to these developments are changes in the general culture of design including the introduction of new design concepts, and the recognition of new contingent relationships with philosophy and the sciences related to these concepts.

1 *What is digital design: an introduction to theory, method and praxis*

By the year 2003 with the *Non-Standard Architectures Exhibition* at the Pompidou Center in Paris, the concept of non-standard, non-normative, non-repetitive design had become a major theoretical focus of this new phenomenon – recognized today as *digital design*. Design media that promoted the non-standard, the antithesis of typologically based normative knowledge, were now being promoted as a major characteristic of digital design.

The concepts of the standard and the normative are part of a deeply embedded cultural logic which underlies the thought and basic procedures of our design thinking and our methods of design. Whether in the form of a numerical expression, or in the materialization of the productive system, these root concepts propagate what might be called the 'logic of repetition'. Implicit in this logical construct is the idea that the module is a formalism that can generate through reproduction; and reproduction, or repetition, of the elemental normative knowledge produced a world of normative order that was so fundamental to the age of machine industrialization. Mitchell, in referring to industrial modernism, argues that the production of buildings that was once based on the materialization of paper-based drawings is now becoming accomplished through digital information (Mitchell, 2005). Buildings are now designed, documented, fabricated and assembled with the assistance of digital means. Within this new encompassing framework that he designates as *digitally mediated design* he argues that the emerging architecture of the digital era is characterized by high levels of complexity; this enables more sensitive and inflected response to the exigencies of contextual aspects such as site, program, and expressive intention than was generally possible within the framework of industrial modernism (Mitchell, 2005). Furthermore, the ability of digital models to connect between design and materialization even in conceptual design stages supports a new depth of contextualization and performative design.

If the new design is in any sense revolutionary, it is so not due to its forms, but to its ability to propose meaningful alternatives to the logic of repetition in the comprehensive historical sense proposed by Mitchell. In our design disciplines this simple phrase represents, among other things, complex phenomena that include the determinism of the concept of function, the questioning of the productive necessity of repetition, or 'standardization', and the basic stability, or instability, of the concept of

types. The syndrome of repetition propagates the value of environmental stability, while the real world presents a different picture of dynamism, constant change, and minute incremental variations. The new design faces this syndrome of the normative, static, and typological and proposes alternatives of discreteness, diversity, differentiation and dynamic evolution. It is this broader cultural transformation of root design concepts that is the paradigm shift of the new design culture.

The rise of a theoretical discourse reflecting the increasing importance of the growing role of digital design in design practice became a seminal issue in the 1990s. During this period, the theoretical discourse around developments in digital design culture became one of the substantive influences upon design and architectural theory. This evolutionary development in design theory appears today to have had the following two streams of influence:

1. The first of these attempted to distinguish digital design as a methodologically unique form of design that was capable of producing uniquely significant results.
2. The second of these theoretical thrusts was the attempt to define the unique content of digital designs.

The works of the 1990s, the literary production, the public events of conferences, competitions and exhibitions, and the resulting design production served as catalysts during this period to formulate the theoretical discourse of digital design. It is to these attempts to identify and characterize the relationships between theory and design in the first digital age that we now turn. These forms of theoretical production will be reviewed in the following section in order to characterize the directions that they represented. In doing so we attempt to clarify how they contribute to crystallizing new forms of design content and attributes for digital design and to formulating a new design methodological agenda.

1.1 The search for new design paradigms

Is digital design enabling new forms of design content, or is this phenomenon primarily a case of designs exploiting digital media? Is the new design characterized by new types of formal shape complexity or can we formulate more intellectually significant distinguishing characteristics? As we consider these questions, we will use examples from architectural design. However, similar patterns of historical transformation can be observed in developments in other design fields such as product and graphic design.

New formal characteristics in design appear to be influenced by the computational facilities of current software that supported advanced types of form generation relative to complex and topological geometries. The impetus towards formal diversity and differentiation may be seen in part as a rejection of the compositional strategies that had become characteristic of much design of the 1980s. Rather than design strategies of hybridization, combination and transformation, design of the 1990s favored material and performative investigation that was capable of producing topologically complex geometries and formal differentiation over the continuity of the design object. Evolved form began to replace complexity and contradiction. The new interest in performative design, tectonics, topological geometry and material expression reflects an implied critique of the formally motivated complexity of the previous generation.

These characteristics emerged in various designs that were realized before and after the millennium. In architecture, the Guggenheim Museum, Bilbao by Frank Gehry was the most prominent catalyst of theorizing new formal directions and postulating new design methods. Beyond the Postmodern sensibility of complexity through 'heterotopia', or complex hybrids, the Guggenheim introduced the complexity of new geometric approaches freed from a priori formalisms, such as linguistic formalisms. Morphogenesis as generation (Kolarevic, 2003) was emerging as a process of 'form finding' or 'emergent form', related to various digitally based generative techniques without either normative formalisms or heterotopic composition. Furthermore, while not strictly the result of digital design, the Gehry office was deeply committed to researching the potentials of advanced digital technologies (Lindsey, 2002). These experiments established precedents for integrating computational systems in the total process of design/materialization/production/construction.

As advances in the integration of computational technologies in design developed during the decade of the 1990s, praxis and theory evolved simultaneously. New approaches and technologies to morphogenesis were accompanied by new directions in design methodology. Among the many theoretical and realized projects of this formative period, the following two (one pre-Bilbao; one post-Bilbao) were among paradigmatic works.

The International Terminal at Waterloo Station in London by Nicholas Grimshaw is an early example of the non-repetitive, 'evolving', continuous linear design themes that were to preoccupy design

experimentation of the period. Its sinuous, curvilinear glass shape was designed using early applications of parametric design techniques that have become a more common phenomenon of contemporary design.

These characteristics of topological form, transformational, or differentiated, evolution of spatial structure, non-hierarchical organization, and complex, hyper-connective spatial conditions became more prominent in later works. Among these, the Yokahama International Port Terminal by Foreign Office Architects (Moussavi, 2003) is a case study in forms of complexity including the emphasis upon what might be termed, 'hyper-continuity', or complex topographical models that were difficult, or impossible, in pre-digital design. These and other designs were being produced in a period when the theory and methods of digital designs were rapidly evolving.

In order to complete the introduction to emerging digital design culture certain of the milestones of the period in digital design literature and events are briefly reviewed below. The major body of theoretical production in digital design has occurred in the past decade. Given the large scale of literary production in this period, an attempt to provide a very brief mapping of this intellectual activity is made in the following two sections on literary production and related events. Rather than providing a comprehensive survey which is beyond the scope of this present paper, an attempt to characterize this body of work, its emphases and achievements is presented in the next section.

In reviewing this material we found that the emphasis on theoretical, as opposed to methodological descriptions, has created a condition of lack of clarity with respect to the methodological nature and contributions of digital design methods. It is this lacuna of methodological categorization and the definition of its potential that is addressed in the later sections of this paper.

1.2 Formulating a theoretical discourse: literary production at the frontier of digital design

Much significant theoretical writing (Kipnis, 1993; Kwinter, 1998, 2001; Somol, 1994, 1999) attempted to re-address key theoretical issues (e.g. 'formal knowledge', 'models', 'representation', etc.) that preoccupied the design community of the last generation, and to redefine these issues from new perspectives. Other works such as van Berkel and Bos (1999) published important writings on changing theoretical and methodological perspectives on design as a research-motivated activity. This new work introduced a body of theoretical concepts such as 'the diagram'

and 'design machines' that were becoming the mechanisms for the transformation from the previous to the present discourse. Like much of the writing of the period, the *emphasis was upon theoretical discourse as related to design, and less upon technical, or systematic, exegesis of methods and design techniques*.

An important threshold was achieved with the *Folding in Architecture* special issue of the journal *AD* (Lynn, 1993). Accompanying theoretically important early pieces by Lynn (1993) and Kipnis (1993) are introductions to philosophical sources, studies of technological innovations and their relevance to design, and descriptions of experimental projects. This combination of diverse theoretical, philosophical, methodological, technical and professional sources was to characterize the discourse of digital design in its first decade. Over the next twelve years, the British journal *AD* followed *Folding in Architecture* with a sequence of special issues on digital design that have made it the most important sustained supportive vehicle for the postulation of the theoretical foundations of digital design.

Among theoretically significant monographs are Lynn (1999), van Berkel and Bos (1999), Rashid and Couture (2002), Rajchman (2000), Oosterhuis (2002), Zaero-Polo and Moussavi (2003), and Spuybroek (2004) each of which are important works by and on leading digital design practices and each volume of which contains significant theoretical and/or discursive content on digital design as a unique form of design practice. Zellner (1999) and Rosa (2003) are characteristic of numerous volumes on digital designs that are collections of short descriptive monographs on selected digital practices. Kolarevic (2003) and Kolarevic and Malkawi (2005) are recent works providing much more methodological and technological content on recent developments in digital design, while Kalay (2004) is a contribution to principles, theories and methods of CAD.

1.3 Celebrating the digital presence: conferences, competitions, and exhibitions

The rapid rise of the volume of both conventional and web-based publication in the past five years indicates, among other things, the theoretical centrality that digital design has come to occupy within design discourse. Promulgating this high level of interest has been a series of international events that, again, demonstrate the centrality that digital theory, methods and practice have come to occupy within design discourse. The FRAC (Fonds Régional d'Art Contemporain du Centre) in Orléans, France has been a center for the documentation, publication,

and exhibition of digital design since 1991. Directed by Brayer and Migayrou, the center has sponsored a yearly series of exhibitions and symposia since 1999 and published a series of books called, *Archilab*, (Migayrou and Brayer, 2001). Two significant publications on digital design were sponsored by the RIBA *Future Studies Project* as part of symposia on digital design (Leach, 2002; Leach et al., 2004). Given their timing, agenda and importance of the participants the works represent a state of the art contribution to contemporary discourse.

As current director of the department of architecture at the Centre Pompidou in Paris, Fréderic Migayrou was responsible for the exhibition, symposium and catalog of *Non-Standard Architectures* of 2003 (Migayrou and Mennan, 2003). This symbolically important event in which a key national museum recognized the significance of digital design was followed by the *Non-Standard Praxis* conference of 2004 chaired by Goulthorpe at MIT as a continuation of the Centre Pompidou event. Theoretical writings associated with these events attempted to define the key significance of the concept, non-standard, as characteristic of a paradigm shift in design thinking. By 2005, many other museums throughout the world had mounted exhibitions of the digital design phenomenon. Among these, an exhibition held at the DAM (German Architectural Museum) in Frankfurt produced an interesting catalog (Schmal, 2001).

What other *supportive institutions* can be identified? The architectural exhibitions at the Venice Biennale in 2000 and 2004 have prominently represented digital designs. The theme of the 9th International Architectural Exhibition in 2004, *Metamorph*, explicitly attempted to theorize the nature of transition and evolution in current theory and practice. The particular theoretical emphasis upon morphogenesis and the general impact of digital design upon design thinking was the subject of one of the catalogs entitled, *Metamorph: Focus* (Forster, 2004).

International design competitions have functioned as a medium for the promulgation of materials and theories of digital design. As such they have drawn the interest and participation of many younger designers and provided a forum for the explicit theorization of digital architecture. In this respect their role is different from the historical mandate of the Venice Biennale. Here the focus is explicitly on the intervention of digital media in design. One of the most significant of yearly competitions is FEIDAD (The Far Eastern International Digital Design Award), a forum that permeates an international selection of diverse works under the general rubric of digital design (Liu, 2005). These volumes also provide

a forum for the publication of writings by the international jury of the competition. The writings, though generally brief, offer certain perspectives that are lacking in the other literature discussed above. The jury is generally composed of an international body of academics who are involved in teaching and researching digital design, working in software production, etc. Thus the emphasis is frequently methodological and pedagogic.

The academic/scientific perspective tends to be unique in its emphasis on formulating the theoretical and methodological aspects of digital design. Much less occupied with the formal innovations that have been such a strong motivating device of the first generation of digital designs, the academic/scientific emphasis presents a much clearer focus upon digital design as a new set of technologies and unique media of design that are transforming our traditional definitions and concepts of design. It is this emphasis the *influence of new media upon design processes and design thinking* (Oxman and Liu, 2004) that characterizes much of the research involvement with digital design and promises to be one of the research contributions to this rapidly evolving field.

1.4 Theory and praxis: the problematic of digital design thinking

As new ideas emerged in digital praxis the need to provide a theoretical framework became more evident. We have observed that the discourse of digital design was strongly motivated by transformations in praxis. As we have seen, this process appears to have been characterized by the attempt to demonstrate the uniqueness of the discourse through a process of 'the transvaluation of values'. In this case, transvaluation took the form of a reinterpretation of root concepts that have been central to the previous theoretical discourse.

We have previously stated that among the agenda of this *discursive period* of digital design have been two important objectives: to demonstrate that digital design is a *methodologically unique form of design*, and to define the *set of design issues and concepts* that were potentially the unique theoretical content of digital design. It is the articulation of these two objectives: the *methodological character* and *conceptual content* (Oxman, 2005) of digital design that we now turn in the following chapter.

Beyond the fact that digital design has passed through a remarkable period of rapid absorption, practical exploration, theoretical production, and some degree of materialization, it appears that the theoretical foundations of digital design as a form of design are still unformulated, and

that its conceptual foundations are still bound up in ideological positions. It is to these issues that we now turn.

2 Towards a conceptual and theoretical framework

Are the recent developments that we have described indicative of fundamental changes in theories, methodologies, and design and production practices? Having reviewed the emerging phenomena of digital design during the last decade, it is apparent that despite the large body of available literature and the high level of theoretical and design production, the methodological distinctions related to these phenomena are not yet formulated. Consequently, it is difficult to determine whether digital design actually constitutes a unique form of design, and if so, how.

This section postulates a basis for formulating a conceptual framework and theoretical models of digital design. This framework functions as a medium to represent the syntax and content of models encountered in the analysis of digital designs. On the basis of this analysis we have proposed *a structured series of models of digital design methodology* that define and explain innovative paradigms of digital design. This representational formulation has also proved to be a productive method in that it has supported the identification, within the mapping of paradigms, of future implications for new and complex relationships between designers, design media, and digital design toolmakers.

2.1 Design methodological concepts as a medium for formulating digital design theory

One of the emphases of recent research in design methodology has been the analysis and formal modeling of designing. A characteristic aim of prominent research (Mitchell, 1990; Lawson, 1997; Cross, 2000) has been the identification and description of the principles and processes of designing, the nature of design knowledge, and the cognitive frameworks of design. One approach to the foregrounding of present and future implications of digital technology can be formulated in relation to the conceptual categories of design research methodology. In the present research we propose that the design methodological research orientation can constitute a conceptual framework for the formulation of a theoretical approach to digital design.

One way in which the clarification of the uniqueness of digital design media can be established is to define the *characteristics and unique properties of design that are emerging in new forms of digital design processes*. The approach of the present research has been to achieve a working taxonomy for the conceptual formulation of digital design through the

analysis and explication of known models of design. In doing so, we define how these models are modified and adapted when considering design with digital media. If such a modeling process can be well-formulated, it can potentially provide an analytical and structural framework that will in itself assist to identify the elements, linkages, relationships, processes and properties of digital design.

In order to present the models of digital design we first propose the development of a taxonomy that can be exploited for modeling digital design. We identify the components of such models of design, their logical structure and morphology. This analytical method provides a means for establishing a generic schema of design models that enables the mapping of variants of form and structure. Following this, and exploiting this generic schema in order to represent recent developments in digital design, we identify and discuss the forms of change and transformation of design models in order to accommodate major design cases of digital praxis. In this way a structured series of models of digital design paradigms are developed.

2.2 Models of design and models of digital design

Early design models attempted to symbolically represent design as a staged linear cyclical process. Gradually this process representation became more particularized taxonomically in order to identify and name the sub-stages and sub-tasks of the design process. However, despite the diversity of nomenclature, certain major classes of design subprocess began to crystallize. These included problem/situation input formulation, synthesis/generation, representation, and evaluation. Certain researchers even suggested that this basic morphological structure was a generic linked set of processes that existed in each of the sequential stages of total design.

By the early 1980s new layers of cognitive depth began to be introduced to design modeling by Schon and his collaborators (Schon, 1983; Schon and Wigging, 1988) who placed the main focus on the designer himself and on the study of design thinking. These models began to be suggestive of cognitive properties that were capable of capturing the complex nature of 'what goes on in the designer's head' (Lawson, 1997). Frequently referred to as 'reflection in action', these models emphasize the interaction of the designer with the problem representation and characterize design as a process of reception (perception)—reflection (interpretation)—reaction (transformation). Schon's conceptual terminology of design as the 'interaction with a visual medium' for 'informing further designing' has still relevance as a concept in models of digital

design. Beyond establishing the central role of human interaction in the formal modeling process, it is significant that *the centrality of the designer can be maintained in models of digital design*. In fact, this concept has profound implications for digital design media in that it implies that *the control of digital processes*, complex as they may be, *is based upon interaction and reflection with the designer*.

What is now becoming characteristic of complex and integrated design systems is the *degree of individual control* provided the designer in digital processes. Thus the growing importance of user interface design, and the emerging significance of a *highly design computation literate cadre of designers*.

2.3 A generic schema of components, relationships and properties

In order to explicate the various components required to model digital design, it is necessary to formulate a symbolic representation through which a basic schema for models of digital design can be developed (Figure 1). In this process, we continue to employ certain of the conceptual distinctions and graphic symbolic conventions that have become well-accepted formalisms in design models (Figure 2).

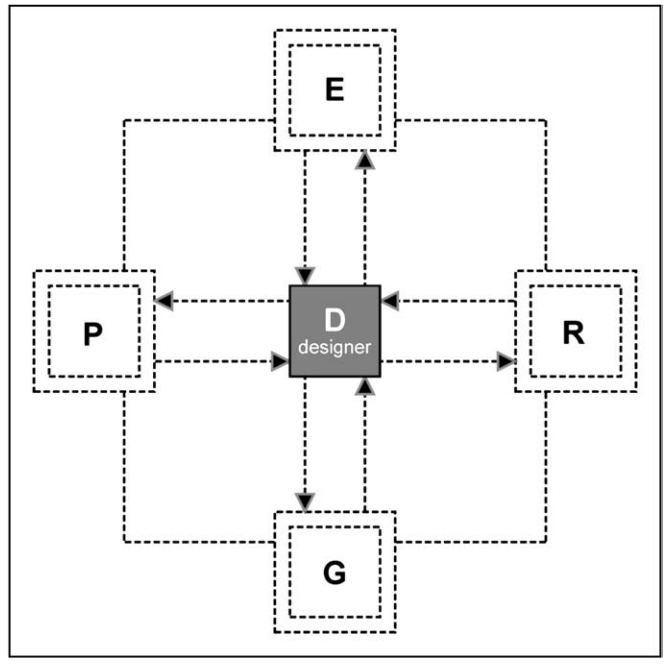

Figure 1 Generic schema

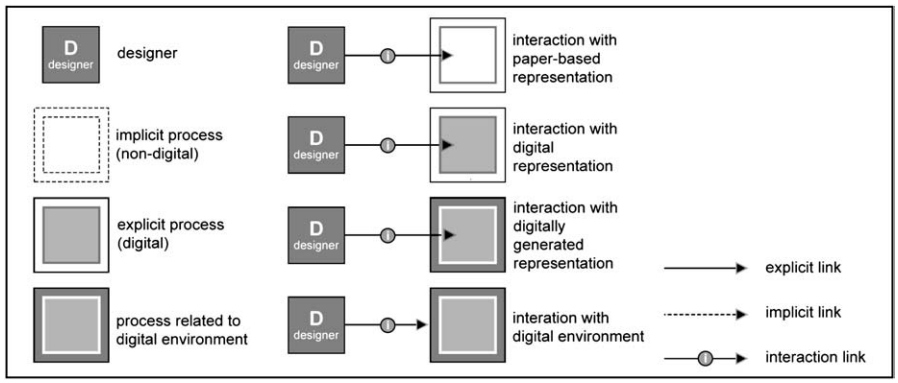

Figure 2 Generic schema: symbols, boundaries and links

2.3.1 The designer

The role of the designer was not systematically explicated in early process models. In digital design, interaction with new digital representational media raises significant qualitative and conceptual issues which require explication. The designer retains the central symbolic position in the design schema. However, the *nature of interactivity* and *type of control of design processes* is treated as highly significant and necessary of detailed qualitative explication.

Digital technology has contributed to the emergence of new roles for the designer according to the *nature of his interaction* with the media. The designer today interacts with, controls and moderates generative and performative processes and mechanisms. Information has become a 'new material' for the designer. These developments are supporting new roles for designers including the designer as a tool builder. The nature of these transformations of the role of the designer vis à vis the character of the interactivity in design sub-processes is defined and symbolically represented in the models by the character of links between the designer and these various sub-processes.

2.3.2 Four components of digital design

The proposed model contains four basic components that represent four classes of the traditional design activities (Figure 1). These are denoted in the schema as *representation*, *generation*, *evaluation* and *performance*.

Representation here is strongly related to the representational media. *Generation* includes generative processes. Generation and interaction with digital form is considered fundamentally different from generation and interaction with the 'free form' of paper-based representation.

Evaluation includes evaluative analytical and judgmental processes. *Performance* includes performative processes related to programmatic and contextual considerations.

2.3.3 Properties: implicit versus explicit

Traditional models of design processes were based on implied, rather than explicit, knowledge. Both generative and evaluative knowledge were not formalized and very often this lack of formalization was associated with intuition and creativity. In a computational view of design the explication of cognitive processes is based on our ability to formulate, represent, implement and interact with explicit, well-formulated representations of knowledge. In digital design significant processes that have frequently been represented as non-explicit in traditional design models must now be considered explicit. What was an implicit cognitive process in the modeling of design in paper-based media has become explicated due to the nature of computational processes in digital design. As a result, the imperatives of computational models and digital mechanisms are contributing to the explication of cognitive processes in generation, evaluation, etc. The modeling conventions accommodate both of these conditions.

2.3.4 Relationships: information and interaction links

Two kinds of relationships between these components have been identified: interactions with specific representational components and links that are the product of information flow.

- *Interaction*

The role of interaction with design representations has broadly been recognized as a fundamental factor in design. Interaction, or interactivity, likewise plays a key role in distinctions between the digital models. Various kinds of interactions with digital media are identified and classified according to the type of interaction between the designer and the representational media. For example, in paper-based interaction the designer interacts directly with the shapes he draws on paper. Interaction with digital media is dependent on specific implementations of computational constructs. Interaction with computational design media requires of the designer a different form of input and level of formalization. These distinctions between paper-based interaction with representations and digital interactions are significant both cognitively and theoretically. Defining various attributes of interaction is seminal for the definition of digital design models.We distinguish between *external interactions* and *internal interactions*. External interactions are traditional types of direct interactions with shapes and forms. Internal

interactions, on the other hand, are related to interaction with digital form *through the medium* of certain digital environments, computational processes, or mechanisms. These may be further distinguished by a certain specific form of interaction. In general, we propose four classes of interaction:

- *Interaction with a free form (paper-based non-digital) representation*

  This type of interaction is typical for paper-based design. In this case the designer interacts directly with a representation of the design object through a sketch, drawing or a physical model to create his design.

- *Interaction with digital constructs*

  This type of interaction is typical for a CAD-based design. In this case the designer interacts with a digital sketch, digital drawing or digital model.

- *Interaction with a digital representation generated by a mechanism*

  This type of interaction is typical of interacting with generative design mechanisms. In this case the designer interacts with a digital structure that was generated by a mechanism according to a set of predefined rules or relations.

- *Interaction with digital environment that generates a digital representation*

  This type of interaction is typical of interacting with the operative part of a generative design mechanism. In this case the designer can interact with the computational mechanism that generates the digital representation.

2.4 The symbol system

The symbol system can be summarized as follows (Figure 2).

- Elements and their individual letter symbols represent the basic components of the model: R = representation and formal content, G = generation, E = evaluation, and P = performance.
- Boundaries and arrows represent interaction type between the designer and the representational media as illustrated in the symbol schema below.
- Links are represented by a line. Lines and arrows explicate interrelation links between the components of the model. Implicit and cognitive links are represented by dotted lines and explicated computational links are represented by full lines.

According to these symbols, a paper-based model can be depicted as presented in Figure 3. The designer implicitly integrates performative

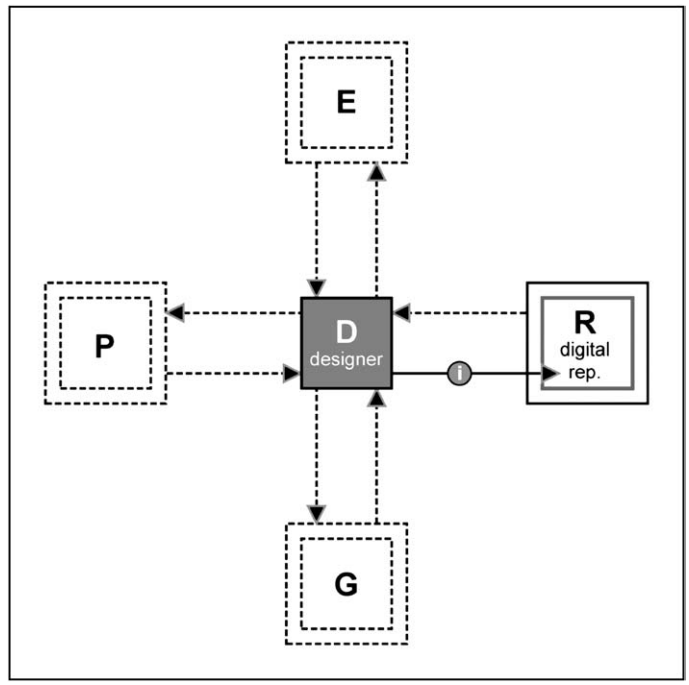

Figure 3 Paper-based model

requirements, generative and evaluative procedures while interacting directly with the formal representation. E, P and G and their linkages with the formal procedures illustrate the implicit part of the cognitive behavior of the designer.

By explicating the role of different types of digital processes employed in representation, generation and performance as well as the information flow and the typical interactions we will identify, explicate and distinguish the different models that currently constitute digital design. Furthermore, this structured approach to modeling the paradigms of contemporary digital design has enabled us to identify implications for future potential directions of development of design in an age of advanced digital design media.

3 Digital design models

The modeling approach provides us with a rigorous medium for the comprehensive structuring and mapping of generic possibilities of digital design models according to various relationships between the designer, his conceptual content, the design processes applied, and the design object itself. The following are proposed as current five paradigmatic classes of digital design models.

(1) CAD models
(2) Formation models
(3) Generative models
(4) Performance models
(5) Integrated compound models

The models demonstrate a *successively structured development* based on the schema presented in Figure 1. The sequential structure of these models is based upon the explication of the components, their associated digital processes and the specific type of their properties. We demonstrate the challenge for reconsideration and redefinition of concepts in traditional (non-digital) design in order to accommodate these digital design models.

The sequence also foregrounds the change and modification in each of the successive digital models. We can observe that in the successive models, non-explicit modules and their properties are made explicit according to the incorporation of certain digital processes. The activity modules and the key components of the basic schema presented in the previous section appear in all models in order to trace their evolution, including their properties, the level of their explication, the different types of interactivity that are associated with them, their information links, and their level of integration.

3.1 CAD model

Early CAD technology marked a departure from paper-based media. In articulating this major shift, traditional CAD models are defined below: descriptive CAD and generation-evaluation predictive CAD.

3.1.1 CAD descriptive model

In traditional CAD the interaction with 2d and 3d formal representations supports the a posteriori automation of design drawings and visual models. The first generations of computer-aided design systems were therefore characterized mainly as being descriptive through employing various geometrical modeling/rendering software. The common use of traditional CAD has been so far in manipulating the graphical representations of digital objects (Figure 4). According to Kalay (2004) it had little qualitative effect on design in comparison to conventional models.

Today, due to new digital techniques, new relationships exist between the physical model and the digital model as a 'dual-directional' process. For example, this is characteristic of the design methodology employed by Frank Gehry which was recognized as a significant design

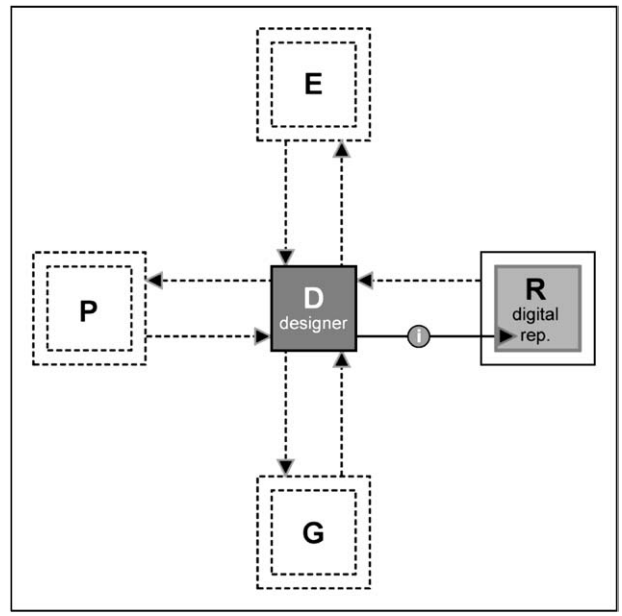

Figure 4 Traditional CAD model

methodological development that is valid even in the conceptual design stage. That is, the descriptive modeling function is increasingly becoming well-integrated with material logic and manufacturing processes (e.g. at the RP level). Following contemporary techniques a physical model can now be generated from digital models supported by various digital *material processing* techniques (Sass and Oxman, in press). Furthermore, the technology has expanded and includes today a variety of methods to reverse the traditional information direction: from data model to physical model. Physical objects can now be captured digitally and translated into digital models and vice versa. Thus the descriptive function of traditional CAD has now evolved towards a seamless integration of virtual and material.

3.1.2 Generation-evaluation CAD model

Beyond drafting, modeling, and rendering of objects, the automation of integrated analysis and synthesis was developed decades ago through the operation of analytical processes on geometrical models. These are described as predictive models as opposed to descriptive models. These types of evaluative analytical processes in CAD are usually associated with cost estimation, structural behaviors and environmental performance etc. Further expanding the data structures associated with current work in areas such as product modeling (Eastman, 1999) allows the integration of various advanced construction level modeling and evaluation software through the different phases of design.

Furthermore, the complex building data structures that support advanced evaluative processes can also support collaboration among different design team participants such as architects and structural engineers. Thus beyond the processes supported by descriptive CAD models, current digital models have also become predictive, and have become explicit rather than implicit as in paper-based design processes.

This model (Figure 5) illustrates the condition in which the CAD representation and evaluation processes are explicated, while other processes remain implicit. For example, the generation module is not explicit and illustrates the fact that generation processes are not formulated or automated and are not linked directly to the representational and the evaluation modules. Explicit links, on the other hand, indicate the existence of a shared database between representation and evaluation. In response to any change in digital representation, evaluations can be made. Any change and modification in digital representation may be re-evaluated due to an integrated database and shared information structure. Interaction is in many ways traditional with the designer interacting with a digital form-representation and CAD manipulation and transformation procedures are employed manually. Note that in CAD systems the designer interacts with the data structure of the representation as

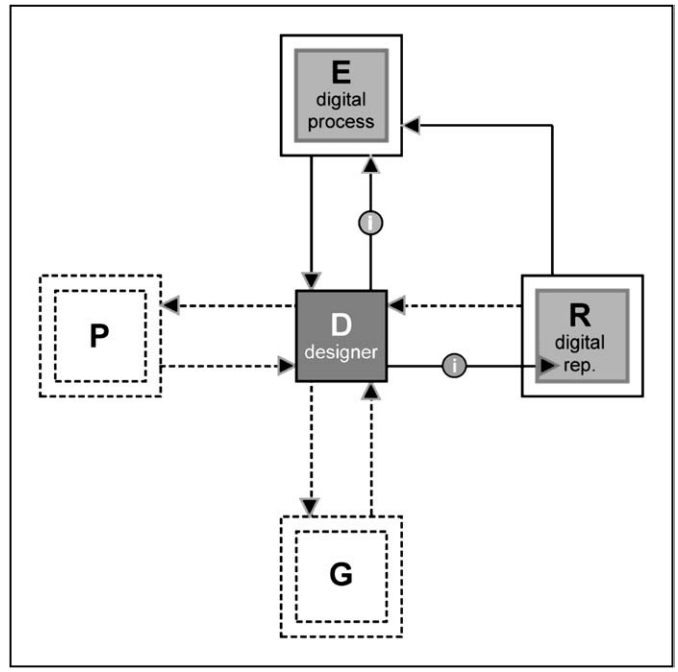

Figure 5 Generation-evaluation model

input to evaluative procedures that are conventionally evaluated visually and/or quantitatively. This process creates a feedback loop of interpretation through the designer who generates appropriate modifications in the representational model.

Despite the fact that representation and evaluation modules are CAD-based and that both are explicated and formulated, the model of design thinking is essentially isomorphic with that of paper-based design in the sense that a sequential linear process of information flow occurs.

3.1.3 CAD descriptive models and their evolution to dual-directional digital processes

Today new relationships exist between the physical model and the digital model as a 'dual-directional' process. For example, this is characteristic of the design methodology employed by Frank Gehry which was recognized as a significant design methodological development that is valid even in the conceptual design stage. That is, the descriptive modeling function is increasingly becoming well-integrated with material logic and manufacturing processes (e.g. at the RP level). Following contemporary techniques a physical model can now be generated from digital models supported by various digital *material processing* techniques (Sass and Oxman, in press). Furthermore, the technology has expanded and includes today a variety of methods to reverse the traditional information direction: from data model to physical model. Physical objects can now be captured digitally and translated into digital models and vice versa. Thus the descriptive function of traditional CAD has now evolved towards a seamless integration of virtual and material.

3.2 Digital formation models

In digital design the centrality of traditional concepts of paper-based representation are no longer valid conceptions for explicating the thinking and methodological processes associated with digital design. Furthermore, in certain formation processes of digital design the formal implications of the concept of representation are negative and unproductive. Digital design has moved away from the static abstractions that are implied in the concept of formal representation. Digital design formalisms are moving towards dynamic concepts that are creating a new definition of the role of representation itself. Advanced digital techniques are not simply changing our modes of design representation; they are forging new bases for design thinking. As the liberation from the conventional logic of representation has occurred, emerging design theory has transformed the concept of *form* into the concept of *formation*.

We no longer represent designs in the conventional paper-based sense. Digital design characteristically exploits emergence-based formation processes in which digital representational media are the enabling environment. This mode, in many ways *replacing the experimental visual nature of the paper-based sketch*, is usually developed through the interactive digital modification of certain formation processes. Digital techniques for the formation of shapes and forms in many cases are the basis for the definition of this model (Figure 6), thus we have termed this model a formation model.

The form generation in this model is based on interaction with an *enabling digital technique* (note the nature of the envelope that contains the visual representation) rather than with the explicit representational structure as in the CAD model. The designer employing techniques such as scripting *interacts with and operates within the non-deterministic logic of the form generative environment* rather than with the explicit representation of a particular form, be it CAD-based or paper-based. *Thus the emergence of non-deterministic design processes is an additional characteristic of emergent processes of digital design thinking*.

In the formation model the *enabling digital technique* is a structured geometrical or formal digital process providing the designer with a high

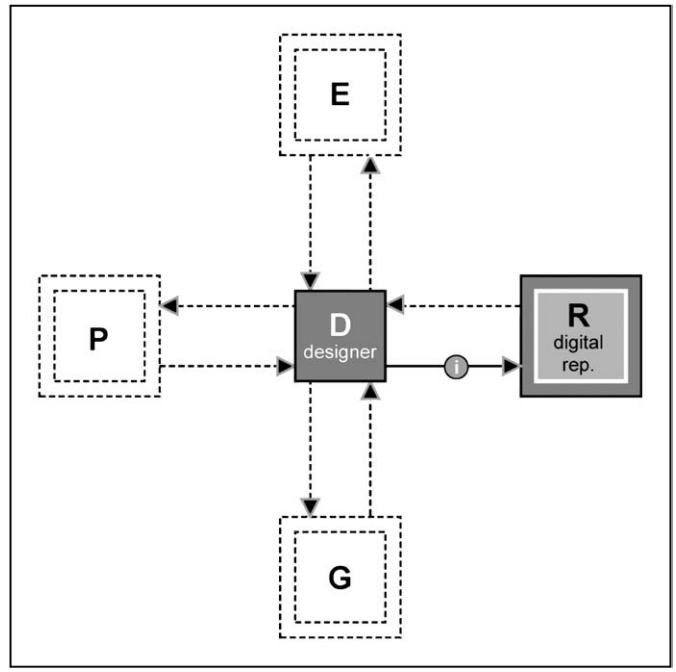

Figure 6 Formation model

level of digital interaction and control. This level of interaction with, and control of, digital formal environments provides a performance of digital enabling that is perhaps the first charactering quality of digital design phenomena. However, it is important to note that despite the sophistication of technology and level of performance vis à vis interactivity with the graphically enabling media, the emphasis is primarily upon the formal/geometrical qualities of designs. Despite this limitation of focus, these graphically enabling media have become a highly sophisticated design sub-area in themselves in which the design media designer becomes a *digital toolmaker*.

We have identified the following sub-classes: the first is termed *topological design* and is based on the exploitation of topology and non-Euclidean geometry in creating design media for formation; the second is termed *associative design* and is based on principles of parametric design and generative components; the third is termed *dynamic design* and is based on animation, morphing and other range of motion and time-based modeling techniques that can propagate multiple discrete instantiations in a dynamic continuum.

3.2.1 Topological formation models

The reconsideration of topology and non-Euclidean geometry as a formal basis for design implemented in digital design has contributed to the exploration of new formal possibilities. Topology is the study of the relational structure of objects rather than of geometry. It is the study of those properties of objects that do not change when homeomorphic transformations are applied. Therefore topological structure can be defined in a variety of geometrically complex forms. Emmer, in *Mathland: from Flatland to Hypersurfaces* (Emmer, 2004) has investigated the role of topology as a new formation process in design.

These design theoretical tendencies have been supported by new software technologies that have opened up a universe of interactive topologically based geometric manipulative possibilities. In such digital design media the static coordinates of shapes and forms of conventional digital media are replaced by computational dynamic constructs including topological surfaces, or Hyper-surfaces. Furthermore, interactions with digital modifiers (nurbs, non-uniform rational b-splines), or modeling operations such as 'lofting' are opening new technologies for the creation and highly interactive manipulation of complex geometrical shapes in design.

Given the dramatic formal characteristics that became associated with these developments, (generically referred to as topological design) these design phenomena were significant in advancing the theoretical and practical significance of digital design in the second half of the decade of the 1990s. New terminology also emerged including hyper-surface design, blob architecture, hyper-body etc. The following designers are among those whose work demonstrates this approach: van Berkel and Caroline Bos, 1999; Lynn, 1999; Oosterhuis, 2002.

In addition to this descriptive terminology, topological design is also associated with a body of theoretical concepts related to the morphology of complexity such as hyper-continuity and hyper-connectivity. References are also made to biological conditions of networked connectivity and rhizome-like complexity.

Thus topological design may be seen as characterizing the first formal statements in a new design philosophical worldview that attempts to accommodate the new complexity of non-linear, networked conditions, and to depart from the more static and typologically deterministic logic and design methodologies of the previous generation.

3.2.2 *Associative design formation models*

Associative design is based on parametric design techniques that exploit associative geometry. There is a difference in philosophy between explicit and associative geometry due to the topological effect of digital environments enabling the reconfiguration of parameters of a geometrical structure (Burry and Murray, 1997; Burry, 1999). In parametric design relationships between objects are explicitly described, establishing interdependencies between the various objects. Variations, once generated, can be easily transformed and manipulated by activating these attributes. Different value assignments can generate multiple variations while maintaining conditions of the topological relationship.

Formal techniques in current parametric and associative technologies today provide design support environments in which the designer can define the generic properties of a geometrical structure within a user-defined framework. In current parametric design techniques complex non-standard geometry can be generated and manipulated. Currently Gehry Technologies is offering *Digital Project*, based on CATIA (a high-end, parametric, automotive and aerospace modeler). Another known commercial system is Bentley Systems' *Generative Components* technology.

The designer in this type of formation model is provided with interaction facilities both to the formal modeling as well as to a set of digital techniques. Furthermore the user can interact with 'integrated inner tools' using scripting methods and tools that enhance design freedom and control. This way the user can control his type and level of interaction with the representational medium, manipulate and refine complex geometries while working in such problem areas as design of structural shape.

This combination of interactivity, transformability and parametrically controlled perturbations that generate discrete structural variations within design formation processes is an emerging characteristic phenomenon of digital design. Parametric systems are becoming cornerstones in the more complex performative digital environments described below. Within the framework of these behavioral characteristics the body of theoretical concepts related to parametric formations includes adaptability and change, continuity, proximity, and connectivity.

New roles for the designer are emerging in exploiting this approach in design. The traditional role of the 'the designer as a user' is extended to 'the designer as a tool builder'. A tool builder can define his own generative components and define their transformational behavior (Aish, 2003).

3.2.3 Motion-based formation models

Approaches to form generation that operate without employing a priori categories of form have required a new definition of the concept of form. Here the distinction between form and formation becomes significant. These technologies appear to have freed the image from traditional concepts of representation. They have enhanced the denial of classical notions of representational conventions such as static space, and have introduced new concepts of dynamic space and form that are producing new kinds of interactive, dynamic and responsive designs.

As a result of the topological generation of form and the use of animation and morphing techniques (Lynn, 1999) new theories of form generation in design have emerged. Motion-based modeling techniques such as key-frame-animation, forward and inverse kinematics, dynamic force fields and particle emission have contributed to new potential for dynamic processes of form generation. Animated models of motion in design generate the articulation of form by reintroducing concepts and techniques of morphological evolutionary states. The designer does not interact directly with the representational medium of the emerging

form. Design interaction is within the interactive framework of the animation media that generates the form.

Various designers have experimented with this approach. For example, for dECOi the issue of representation is taken to a point of liquefaction. Goulthrope (1995) of dECOi, in his *Ether/I* project, a tribute to the choreographer William Forsythe has experimented with new techniques of creative formal production such as video capture of traces of dancers' movements. Another example is *Dynaform* designed by Bernhard Franken. This work demonstrated how the dynamics of forces produce the motion and particular transformation of form. This design strategy utilized special effects programs borrowed from the film industry. These programs have the ability to simulate, following physical laws, the changes in the shape of an object when subject to force fields. In an experimental configuration they defined the basic object, its form generating rules, specific boundary conditions and forces by translating the task specifications and the given spatial context. Using this method, the design was developed through an interactive process of parametric change.

3.3 Generative design model

In CAD the designer deals with the geometric structure of a priori design objects. By contrast, digital formation models, as we have just seen, provide enabling design media for geometrical and topological control of variant formal generation within conditions of topological control. Geometric aspects of structural relationships are defined; however, formal qualities are not predefined. Thus formation precludes explicit formal representation in the conventional sense of visual design thinking.

Generative models of digital design are characterized by the provision of computational mechanisms for formalized generation processes (Figure 7). This is a subtle but important distinction. Here, as compared to formation models, the designer interacts with the generative mechanism. The generative model is the design of, and interaction with, complex mechanisms that deal with the emergence of forms deriving from generative rules, relations and principles. Shapes and forms are considered to be a result of pre-formulated generative processes. Interaction has a major priority in this model. In order to employ generative techniques in design, there is a need for an interactive module that provides control and choices for the designer to guide the selection of desired solutions.

Currently there is a rich theoretical body of research-related applications of generative models. Two main distinct current sub-approaches are shape grammars (Stiny, 1980; Knight and Stiny, 2001) and

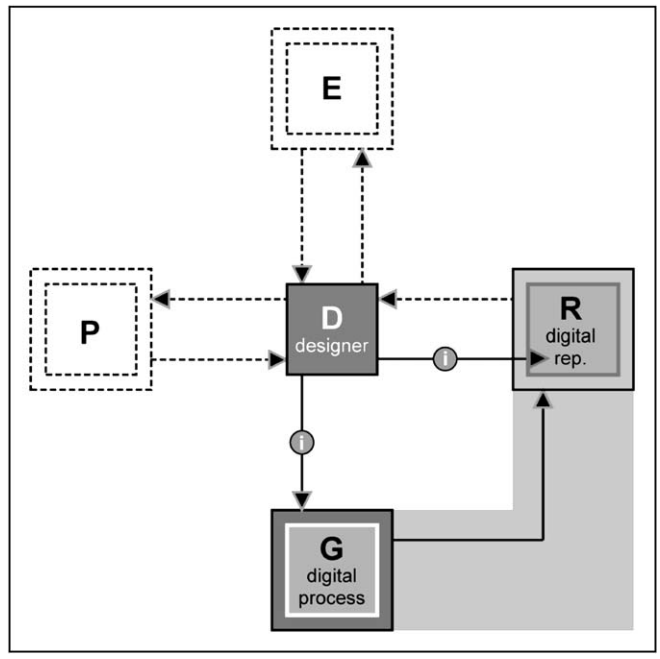

Figure 7 Generative model

evolutionary models. Shape grammars are mathematical expressions for computational mechanisms that drive shape generation processes through transformational rules. Shape grammars are well-known in the design research literature. Evolutionary form-generation techniques are based on evolutionary models of natural generation that can be applied to generative processes in design. We have as yet no examples of compound models combining generative mechanisms in formation models, however, this combination is theoretically possible.

3.3.1 Grammatical transformative design models

Shape grammar as a generative mechanism based upon formal compositional rules is perhaps the most interesting case to examine the problematic of a priori formal content in digital design. Currently, with the change of design focus from spatial composition to tectonic and material qualities, emergent properties of tectonic and morphological design content are becoming incorporated with the mathematics of grammars. As such, shape grammars are presently considered one of the potentially significant models of generation for digital design.

The type of interaction with the generative mechanism is a critical issue in designing a generative system in digital design. Shea (2004) in her work has demonstrated the potential of such an approach in digital

design generation. Grammar definitions here adapt a more abstract, less compositional and more topological character. Her computational system is based upon three-dimensional aperiodic spatial tiling and is an important contribution in the direction towards more topological and less compositional grammars. It is based on computational implementation of the mathematical description of the tiling material as a basic generative grammar related to shape-grammar principles and is employed as a generative tool for design.

3.3.2 *Evolutionary design models*

In an evolutionary model of design, *form emergence* is considered to be the result of an evolutionary process. Evolutionary techniques have been part of a long research tradition exploring computational mechanisms of form generation. Form generation is derived from an internal genetic coding that replaces traditional interaction with the form itself. There also exists a significant body of theory dealing with problems of emergence and the behavior of complex systems as related to evolutionary models.

Genetic algorithms have become a major tool in various research areas. John Holland is the founder of the domain of genetic algorithms. These are parallel computational representations of the processes of variation, recombination and selection on the basis of fitness underlying most processes of evolution and adaptation (Holland, 1992). Genetic algorithms were first employed in a problem-solving and optimization context in which stated criteria and goals were defined and controlled by a fitness function. In this type of automatic generative process there was no interactive consideration. However, in design the provision of interactivity and the formulation and the type of interaction of a certain generative mechanism are essential.

In genetic algorithms, the populations of alternative solutions in generative processes are seen as key components within evolutionary systems. In this approach, genetic form evolution is based on rules defining the 'genetic code' for a large family of similar objects. Variations are achieved through processes of 'reproduction' through gene crossover and mutation. An interactive exchange and change of information governs processes of morphogenesis. The main issues in using genetic algorithms in design are to define a set of generative rules, and to define their evolution and development such that they can be mapped to a specific design context. In evolutionary design the candidate generated forms can be evaluated on the basis of their performance in a simulated environment.

Other evolutionary models of nature, such as biological models of evolution are currently beginning to play a role in digital design especially

those that are related to concepts of morphogenesis (Hensel et al., 2004). Generative design that is based on biological metaphors is associated with D'Arcy Thompson's, 'On Growth and Form' and Gould's, 'The Structure of Evolutionary Theory' (Gould, 2002). These present a non-mechanistic theoretical view of generation, adaptation and evolution of living organisms that is furnishing models for design. Evolutionary systems based on morphogenesis produce properties related to differentiation and heterogeneity and these are perhaps among the two of the most significant properties of digital designs today.

3.4 *Performance models*

Performance-based design can be considered as a process of formation that is driven by a desired performance. Performance-based models of design utilize digital technologies that support the generation of form resulting from design performance. Kolarevic (2003) described the inadequacy of existing analytical CAD software in conceptual design, and discussed the development of software that can provide dynamic processes of formation based on specific performance objectives. Performance can be defined as a formation technique or a generative process the variants of which are parametrically defined by the problem conditions, site, program, etc. This is a unique compound model of design, often misunderstood as simply an evaluation model.

In performance-based design the object is *generated by simulating its performance*. The form is generated according to desired performance, or behavior, of a design object. Under this category we have presented two sub-classes: performance-based formation and performance-based generation models of design.

3.4.1 *Performance-based formation models*

Formation-based design can be regarded as performance-based design when digital simulations of external forces are applied in driving a formation process (Figure 8). Design performance may include among the following parameters: environmental performance, financial cost, spatial, social, cultural, ecological and technological perspectives. Performance-based design employs analytical simulation techniques that produce detailed parametric expressions of performance. These in turn can produce formation responses to complex classes of performance requirements.

The design of the Greater London Authority Headquarters building (2002) by Foster & Partners demonstrates this approach. In employing performance-based techniques, such as analysis simulation programs,

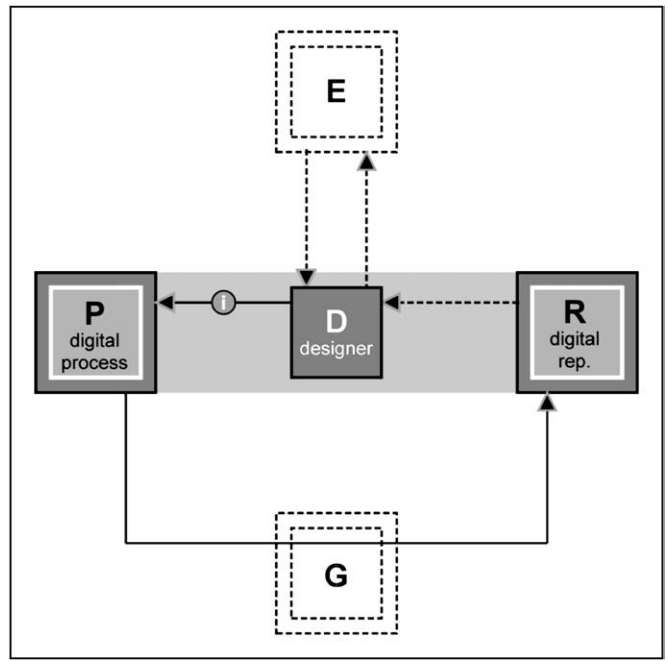

Figure 8 Performance-based formation model

the optimization of energy and acoustical performance was achieved while the surface of the curvilinear façade was minimized. Another example is the Swiss RE building (2004) also designed by Foster & Partners, in which environmental performance techniques were employed to maximize the amount of natural lighting and ventilation in order to reduce the building's energy consumption. The geometry of the aerodynamic shape was formed in order to respond to specific criteria of the performance simulation. As a result of this new design method, the 180 m, 40-storey tower presented a radical departure from the conventions of traditional high-rise office building form, shape, internal organization, fenestration and performance.

In design the external influence of forces can also be applied to inform complex behavior of a model that can be deformed and transformed. This may be relevant to dynamic objects where dynamic simulation can be computed considering environmental influences as the driving forces.

3.4.2 Performance-based generation models

Performance-based generative design is based on generative processes driven by performance and potentially integrated with formation processes. This develops in the direction of the ultimate condition of *integrated enabling digital design media*. Forces in a given context are

fundamental to form-making in digital design. External forces may be considered as environmental forces including structural loads, acoustics, transportation, site, program etc. Information itself is also considered as an external 'force' that can manipulate and activate responsive digital design processes that are transparent to the designer.

In a performance-based generation model (Figure 9), data of performance simulations drive generation and/or formation processes in order to generate the form. The designer can interact with the three modules, defining the performance criteria in the performance module, defining the generation in the generation module and interacting directly with the digital representation.

An example that suggests the important future potential for integrating performance-based with generative design tools is described by Shea et al. (2003). They describe a structural generative method, integrating a generative design tool, eifForm, and an associative modeling system, Custom Objects, through the use of XML models. The system integrates grammatical shape generation, performance evaluation, behavioral analysis, and stochastic optimization. The method is capable of generating performance-driven design of engineering structures, based on

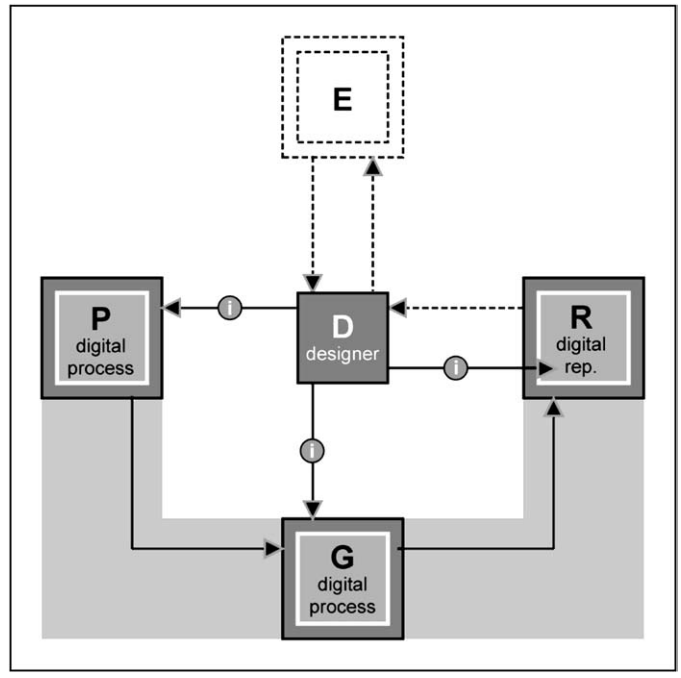

Figure 9 Performance-based generation model

structural and morphological principles. They illustrate an example demonstrating the generation of a set of 20 interrelated roof trusses with seven unique spans initiated by a parametric model of a saddle-shaped stadium roof in Custom Objects.

In digital design concepts that are associated with performance-based animation can also be found in Lynn's 'New York Bus Terminal' (Lynn, 1999). This project is an example in which a particle system is used to visualize the gradient fields of attraction and flow patterns present on the site. These were created by simulating force fields associated with the movement and the flow of pedestrians, cars and buses across the site.

3.5 Compound models

Compound models represent a class of future paradigmatic digital design media that have important potential implication for future design media. Compound models are based on integrated processes including formation, generation, evaluation and performance. Performance simulation, generative and formative processes can be integrated into digital design media. These forms of integrated design media are ultimately the future objective of all compound integrated digital systems (Figure 10). Ideally they will provide interaction with any activity module with the data and information flow in multiple directions. These may be thought of as a *compound integrated network of enabling design media*.

4 Summary and conclusions: design in an age of digital media

This schema of five paradigmatic models has presented an interpretation of digital design in which the methodological characteristics of these paradigms have been formulated relative to tradition theoretical concepts of design and to traditional models of design thinking. These models include the *dual-process CAD model*; *formation*; *generation*; *performance*; *performance-based formation* and *performance-based generation* and finally the *compound integrated model*. These models have demonstrated the growing sophistication of digital design media, their ability to function as integrated and interactive design media, their increasing impact through the total length of design from the conception process to the construction process, and their new role for the designer as toolmaker of customized design media.

The impact upon design of the first digital age has been significant in the theoretical, technological, and methodological senses. We will attempt to summarize various types of impacts as they have emerged through

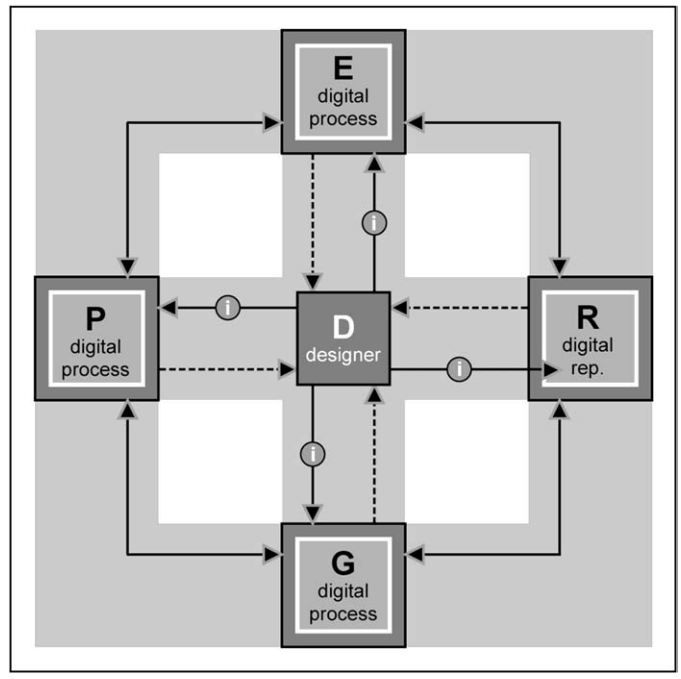

Figure 10 Compound model

our research, to suggest certain of the future implications of these developments, and to sketch some broader aspects of thought and procedure that characterize the emerging new worldview of digital design theory.

4.1 Formulating the nature of digital design thinking

As digital methods, tools and techniques have become central to the design process itself, we are witnessing the emergence of novel processes of mediated design which challenge certain of the cherished assumptions of traditional design theory. As we have seen the concepts of representation, so central to design theory, have been transcended and the concept of design as the purposeful and goal-oriented manipulation of symbolic representations has been virtually abandoned.

New orientations to the explication of the procedural and judgmental aspects of design as performative factors in morphogenesis has introduced a situation in which the new designer has become adept at juggling the *multiple forms of data and images* that are conventionally represented in today's digital design environments. Far beyond Schon's characterization of visual reasoning as a 'dialogue with the materials of the problem' and 'backtalk' from visual images, the intelligent and compound processes of integrated digital design media create a completely novel view of design thinking that justifies the uniqueness of the term, *digital design thinking*.

Digital design thinking is non-typological and non-deterministic in supporting and preferring the discrete and differentiated over the generic and the typological. More than simply a set of formal preferences, or the abandonment of traditional approaches to formal and typological knowledge (e.g. formal languages, typological classes and generic design, design cases, etc.) it explores new forms and relationships between the designer, image, and information. In this case, the 'shock of the new' is not simply in the discovery of new formal vocabularies, but in the establishment of new approaches to design. Here integration, non-formal morphogenesis, and parametric formation, etc. provide new avenues for design thinking. With respect to certain of the root concepts of conventional design theories, the implications of these transformations of models of digital design thinking have revolutionary implications.

4.2 New roles for new designers

Beyond any doubt digital design appears to be becoming a mainstream phenomenon and the theory of digital design appears to be one of the most active and significant subjects of theoretical discourse. This is particularly true of architectural design, but the digital revolution is increasingly influencing all of the fields of design. If we speak of new models of design and novel processes of digital design thinking, are these valid for the majority of the design community, or is there emerging a digital design elite?

As digital design media become more complex and more demanding with respect to knowledge of multiple types of software, knowledge of scripting languages, and the manipulation and maintenance of complex data models, a new generation of digital design specialists is emerging. This is particularly the case today with parametric systems all of which require specialist knowledge in order to operate and maintain them. The thought of the designer as digital toolmaker reflects both the potential for customizing digital design media as it does the necessity for specialist knowledge needed to operate such media. So presently the idea of a class of 'digerati', or digital *literati* as advanced digital systems designers appears to be an accurate description of the contemporary situation.

4.3 Digital design theory and its scientific and philosophical directions

Perhaps the most challenging of the conditions created by the emergence of new technologies of digital design within the last decade has been the simultaneous emergence of new theoretical and philosophical frameworks that constitute the intellectual foundations of digital design. These range from philosophical foundations to cross-disciplinary

collaborations that are forming the world-view within which digital design theory is currently being crystallized. Many of the conceptual terms that have been applied in this research to characterize digital design such as non-linearity, inter-connectivity, continuity, networks, dynamism, the diagram, design machines, etc.) have their sources in Deleuzian philosophy. The idea of attributes of hyper-connectivity and non-hierarchical structures of organization are among Deleuzian theoretical constructs that have exerted a great influence on theorizing digital design and related subjects. These theoretical constructs have multiple forms of influence upon design practice beyond discourse, even including the influence upon spatial design concepts of new forms of continuity, and new concepts of indeterminate environments.

Within the framework of the cross-disciplinary connections to the biological sciences, particularly with respect to new theories such as complexity theory, chaos, emergence, catastrophe theory, and bio-mimetics are now related to fields of emerging technologies from a research perspective.

4.4 Complexity

Despite the fact that many, so called, digital designs are characterized by formal complexity, complexity is not necessarily a defining characteristic of digital designs. However, more than any other concept, understanding and accommodating complexity appears to be most characteristic of digital design as an approach to design. It is *supporting complexity* that is the mandate of design in the second digital age.

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