D-MES: Conceptualizing the Working Designers

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D-MES: Conceptualizing the Working Designers

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Abstract: Domain-independent design theories grounded on formal frameworks are of interest for a wide spectrum of professional and academic fields, including design education, design management and innovation strategy. While much attention has been paid to the modeling of the specification process of an artifact, less attention has been paid to the modeling of the creative social interactions involved in the process of designing. There is still a need for conceptual approaches that could further integrate the creative, collective, cognitive and emotional aspects of design. This paper aims to develop such an integrative view by relying on the Memory Evolutive Systems (MES) (A. C. Ehresmann and Vanbremeersch 2007). Based on a conceptual mathematical domain named "Category Theory," MES provide a relational approach for studying evolutionary, multi-scale, multi-temporality and self-organized systems. Using the MES approach, we develop a conceptual framework which encompasses the various phases of a design process and considers how it is directed by the multiple mental and social interactions between different actors. Our approach, named D-MES, extends prior research by providing a formal account of how various entities can operate in parallel to develop creative combinations of new shared objects and processes of different levels of complexity throughout the design process. An illustration is provided in the case of garden design.

Keywords: Design Theory, Evolutionary Design Models, Design Team Mental Models, Memory Evolutive Systems

Introduction

Over the last decades, many generic design theories have contributed to a better understanding of design principles and practices, and have shown how design can be used by a widening range of teachers and professionals, now including business and innovation strategy. Among the broad range of theoretical approaches which participated to this development, many of them drew on formal or mathematical frameworks (Hubka and Ernst Eder 1987; Suh 1990; Takeda et al. 1990; Hybs and Gero 1992; Simon 1969; Braha and Reich 2003; Reymen et al. 2006; Hatchuel and Weil 2008). The main contribution of these approaches has been to abstract from particular design domains to provide general terminologies that describe the process of designing, whichever it might be.

Still, while much attention has been paid to the modeling of the specification process of an artifact, less attention has been paid to the modeling of the creative social interactions involved in the process of designing. Some streams of research, like the "cognition system" approach (Hutchins 1995), the "design team mental models" approach (Cannon-Bowers, Salas, and Converse 1993; Badke-Schaub et al. 2007; Dong, Kleinsmann, and Deken 2013) or the "co-design" approach(Sanders and Stappers 2008) have focused on such collective phenomena but they did not provide formal accounts so far. As a result, there is still a need for generic design theories that could better formalize the operations and structures underlying the creative, collective, cognitive and emotional aspects of designing. Lacking such an understanding, there is a risk of overlooking crucial aspects of collective design practices, for instance the role of unconscious and inaccessible processes (Badke-Schaub and Eris 2014).

In our view, one important difficulty lies in considering the formation of a shared memory, robust but flexible, and allowing various entities intervening in the design situation to operate collectively, while preserving each singular view and dynamics over time. For instance, in garden design, knowledge about matter and texture is crucial to complete a fine design work. Still, clients are often unaware of how textures might be used as creative materials (*e.g*. composing the textures of barks with those of leaves) and designers may want to educate them to these aspects. In such cases, discussions about textures can lead to rich interactions between clients and designers. It may even occur that clients, who develop their own understanding of garden textures during the design process, conversely modify the way designers were thinking about textures, leading to creative and surprising outcomes. In other words, a design process produces more than an artifact and also involves collective knowledge creation, including the formation and sharing of new mental objects, emotions and rich evocations.

In this paper, we address these issues by developing an integrative mathematical approach to the collective process of designing considered as a transformative process of a relational “design system.” We base our approach on the *Memory Evolutive Systems* (MES), a mathematical framework developed by Ehresmann and Vanbremeersch (2007), which provides a formalized yet essentially qualitative language to model the transformations of a self-organized multi-scale system. Our research goal is to use MES to develop D-MES, a particular MES (with a “D” for “Design”), and provide mathematical notions which can be used to model how various entities can operate in parallel by both shaping and relying on a robust but flexible memory to develop creative combinations of new shared objects and processes of different levels of complexity throughout the design process. Doing so, we aim at reaching a high level of expressivity and generality, which does not necessarily mean developing a computable model, but rather using mathematical thinking to elaborate and invent new notions which could possibly enrich design theory. For instance, we will show that the notion of “archetypal core,” which defines a higher subsystem of the design system memory, can account for crucial collective aspects of design, including emotional, unconscious and inaccessible processes.

Our paper is organized as follows: in the first section we briefly present the theoretical foundation of our research. The subsequent sections detail the key notions analyzed in D-MES which are: *design situations*, *design memory* and *design activities*. An illustration in the case of garden design is then given, before the last section concludes the paper and provides insights for further research.

Theoretical Foundation

The MES approach was first introduced in the nineties (A. C. Ehresmann and Vanbremeersch 1991) in order to develop mathematical models for evolutionary, multi-scale, multi-temporality and self-organized systems. Applied to natural or social systems, a MES represents the successive configurations of the system, *i.e.* the states of its components and the relations among them around a given time, by *categories* and the change between them by *partial functors**.

A *category** is defined as a *graph** – a notion which has been widely used to represent *networks* in many disciplines including design theory – with a supplementary structure, namely an internal law to compose successive arrows, or “paths” (see Figure 1), satisfying some axioms, in particular an *associativity* axiom which means that a path has a unique composite. In a “concrete” system, the idea is that two paths are “functionally equivalent” if they have the same composite. This presentation of categories via graphs follows that given by C. Ehresmann (1965). It is not the most usual one, but it emphasizes the diagrammatic and geometric nature of the theory, which will be of great interest for our present research goal, namely representing the operations and structures underlying collective design processes.

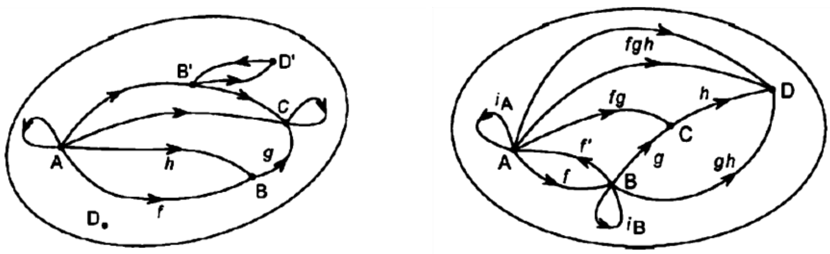

Figure 1: A graph (on the left) and a category (on the right).
Graph: the vertices of the graph are represented by points such as A, B, B'…
The edges are represented by arrows such as *f* (not all the arrows in the figure are labeled).
Category: two successive arrows of the underlying graph have a composite. For example, the arrows *f* from A to B and *g* from B to C have a composite arrow *fg* from A to C so that each path (*f, g, h*) has a unique composite *fgh*.

"Category Theory" (CAT) is a conceptual and contemporary mathematical domain (Eilenberg and Mac Lane 1945; Mac Lane 1971)[1], which allows unifying the underlying constructions that mathematicians use at work (*e.g.* sub-structures, quotient structures, products, sums). Traditional approaches to categories therefore search for well-behaved categories which could be entirely characterized in being (*e.g*. topos). Applied to modeling, such approaches tend to develop an external point of view of the invariant structure of a system over time, which can be problematic when trying to integrate *becoming* and *emergence*.

While using notions and tools defined in CAT, MES offer a dynamic approach that focuses more on the *becoming* than on the total *being* of a system. At this end, a MES does not represent a system by one category, but by an *evolutive system**: it is a family of categories indexed by time which represent the successive *configurations* K_t of the system, and, connecting them, *partial functors** $k_{tt'}$ from K_t to $K_{t'}$ for $t < t'$, named *transitions,* representing the change from t to t' (see Figure 2). By thus describing the changes of configuration of the system between two instants, with possible loss or addition of new elements, it makes it possible to develop an internal point of view and to acknowledge that, by nature, the *becoming* can, neither be described *in extenso,* nor reduced to combinations of local operations.

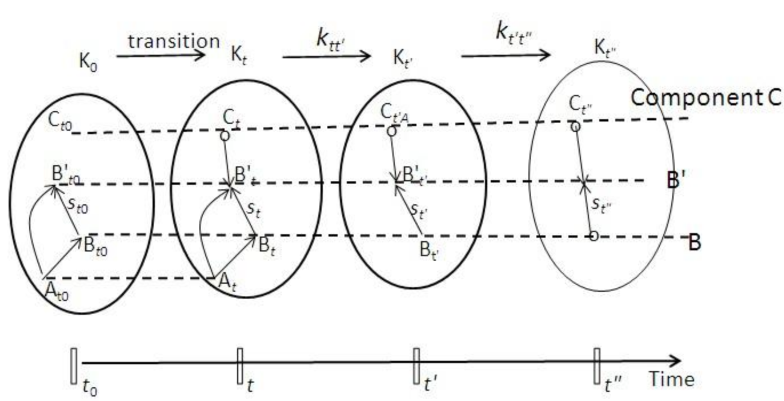

Figure 2: An evolutive system.
The figure shows several successive configurations of an evolutive system K, beginning from an initial configuration Kt_0 at time t_0. The transitions between the successive configurations are partial functors between configuration categories K_t.
A component C is a maximal family (C_t) of objects of K_t related by transitions.

[1]The basic mathematical notions of Category Theory and Memory Evolutive Systems that we use in this paper are followed by * and detailed in the Appendix.

One of the main features of CAT is that it is "relational,” meaning that the *objects* are considered through the *relations* that they share, which are represented by the arrows (also called “morphisms” in categories). Thus the MES approach helps building *relational models* of systems, be they cognitive, biological, or social. A *component* C of the system (*e.g.* a member of the society, or a social group) is represented by the family of its successive states C_t in the successive configuration categories where it exists (hence it is a maximal family of objects of successive configurations connected by transitions). And the *links* between components, which represent the relations that components share over time between each others, are defined similarly as maximal families of arrows connected by transitions.

A system may have a hierarchy of components; for instance, a social group is represented by a component which is more complex than its different members. To account for this, the configuration categories of a MES are *hierarchical** so that the MES has components of different *levels of complexity*; the idea is that a component C of level n+1 is a combination of at least one *pattern* P of interacting components of level $\leq n$, so that C alone has the same operative role than the pattern acting as a whole. It is modeled by the categorical operation *colimit**: C is the colimit of P (see Figure 3). Over time, the decomposition P of C may change progressively (or even abruptly for multifaceted components, cf. Section 2.3) while C keeps its own “complex” identity. For instance the membership and internal organization of an association may vary while the association as such subsists.

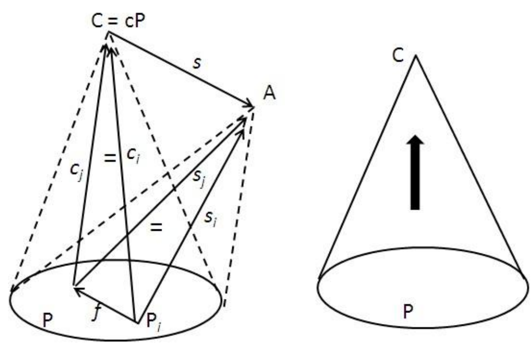

Figure 3: A complex component C and its abbreviated notation.
(C is the colimit cP of a pattern P of interconnected lower level components)

As shown by Figure 4, the configurations of a MES evolve and new components of higher levels of complexity may appear over time. Let us note that the components of a MES can represent entities of any kind, ranging from molecules and cells in a biological system (*e.g.* neurons in a neural system), to artifacts, procedures and processes, individuals and teams, mental objects and internal feelings in a social system.

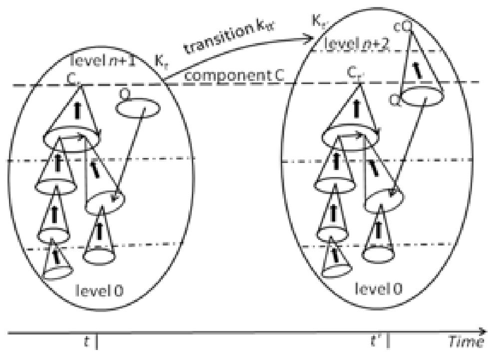

Figure 4: Evolution of the configurations of a MES described by a hierarchical evolutive system.
A new component cQ of a higher level of complexity is added through the transition $k_{tt'}$.

Still, the MES approach does not only describe the system and its changes over time, but also studies how the dynamic of the system is *internally* organized. It therefore combines the modeling of *local dynamics* with the modeling of a *global dynamic* by formalizing how the latter is modulated by the cooperation and competition between internal agents acting as “co-regulators” which operate in parallel with different timescales. This framework thus describes the successive configurations of the system at each time *t*, its transformation over time, including the loss of objects and the formation of radically new objects or processes, as well as how these transformations occur through the interactions of the co-regulators. In particular, it provides mathematical results which explain how the co-regulators both shape and rely on a flexible long-term memory, and may develop a higher part of this memory, named “archetypal core” which acts as a flexible internal model. In the following, we will argue that albeit poorly conceptualized by past research the archetypal core can be a key notion for design theory.

In the sequel, given a particular design system, we model it by a MES named D-MES, more simply denoted by D. Let us now consider how *design situations, design memory* and *design activities* can be defined and articulated within this framework.

Design Situations

As noted by past research (Schön 1983; Reymen et al. 2006; Visser 2009) “design situation” is a key concept in the design literature, especially in design theory, and refers to the situated and embodied nature of all design activities. The concept of design situation thus encompasses the full context of environmental objects and events – including past, present and future – as both existing by themselves and/or internally experienced and shaped by entities, which might be humans or non humans, such as machines and computers, for instance.

Configurations of a Design System

Given the design system D, we define its “design situation” at a time *t* by the *configuration* category D_t of D at *t*, namely its organization consisting of the state of all the *components* and links between them existing at *t*.

This design situation evolves over time, the changes from *t* to *t’* being modeled by the *transition* functor which maps the state of any component C of D at *t* to its state at *t’* (if it still exists at *t'*). A c*omponent* C is given by its successive states while it exists. As already said, C is thus defined as a maximal set of objects of the categories D_t that are connected by transitions.

Hierarchy of Components of a Design System

As all the components of D do not have the same complexity, the *hierarchy of components* distinguishes between simple and complex components of different *levels of complexity,* where a complex component is a combination of lower levels components acting in a coordinated way. Thus a component C of level n+1 admits a decomposition in at least one pattern P of interacting components of levels ≤ n so that C and P have the same operative role within the system. Formally, C is represented by the *colimit** cP of P.

When considering components such as materials, this for instance accounts for the fact that designers often manipulate elementary objects to form more complex ones. It also allows distinguishing between a group of designers interacting informally (pattern P) and the fact that it can be institutionalized as a formal design team C (represented by cP) which will exist and act as such, despite the possible departure of some members and the arrival of new ones over a certain period of time.

Over time, the number of levels within the system may increase with the formation of more and more complex components. As shown by Figure 5, this implies considering not only an evolutive system, as described above, but a "hierarchical evolutive system."

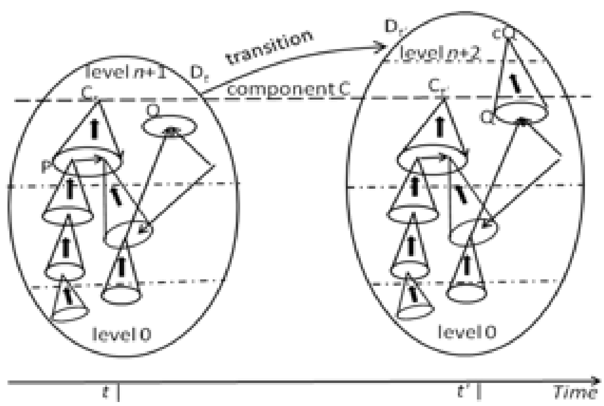

Figure 5: The underlying Hierarchical Evolutive System of a D-MES

Multifaceted Components: Multiplicity Principle

An important notion is the concept of *multifaceted components**. A multifaceted component is a complex component C which possesses multiple decompositions in structurally different and non-connected lower level patterns through which it can switch, while preserving its own complex identity over time. The "*Multiplicity Principle"** (A. C. Ehresmann and Vanbremeersch 1996) asserts the existence of multifaceted components. It gives a kind of *flexible redundancy* to the system, which has been proved to be a necessary condition for emergence and creativity (A. C. Ehresmann and Vanbremeersch 1996).

Complex Identity of a Component

As shown by Figure 6, a component C of the design system D is characterized by its *complex identity* in the system which holds over a certain period of time despite possible internal changes in the inner composition of C between successive states. A lower level decomposition P of C at t (so that C is the colimit of P in D_t) may vary over time; for instance the members of a group C can vary while C (the group as such) preserves its "complex identity." And for a multifaceted component, P may even switch to a structurally different decomposition Q of C while C keeps its identity.

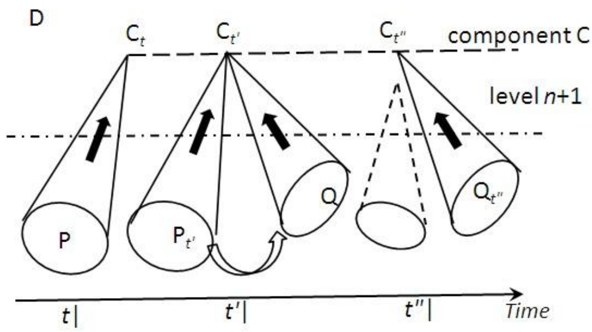

Figure 6: Complex identity of the multifaceted component C

From a philosophical point of view, the complex identity of a component of the system reflects its capacity to actively "persevere in its being"[2] rather than to exist as an isolated and static substance. Thus, components are in an on-going process of individuation and their internal composition may evolve over time.

Decompositions and Ramifications of a Component

A *ramification* is an iteration of the decomposition process of a component (see Figure 7). Whereas a *decomposition* of a component C refers to any pattern of interacting components of lower complexity levels which C binds (*i.e.* C is its colimit), hence acting as a "whole" in the same way as C by itself, a *ramification* of C refers to a chain of decompositions: first of C, then of each component of one of its decompositions, and so on down to the lowest level. One object C can thus have both multiple decompositions at a lower level and still more multiple ramifications down to the lowest level.

Order of Complexity of a Component

While the distinction between simple and complex components is quite usual, especially in system theory, the MES approach characterizes the complexity order of a component through the length of its ramifications Formally, the *complexity order** of C is defined as the smallest length of a ramification of C (see Figure 7), thus measuring the smallest number of steps needed to re-construct C from the lowest level up, by successive combination processes. This notion could be compared with Kolmogorov-Chaitin complexity of a string *x* which is the length of the shortest program that computes *x* and halts (Shiryayev 1993).

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[2] « *Each thing, as far as it lies in itself, strives to persevere in its being* ," Spinoza, *Ethics*, 1677, part 3, prop. 6

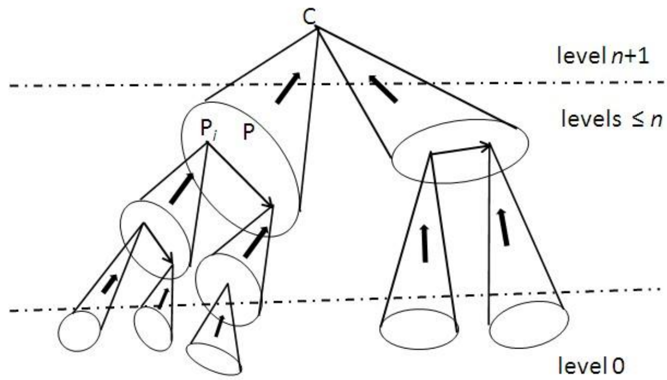

Figure 7: Complexity order of a component C.
The complexity order of C is the smallest length of a ramification down to level 0

Simple and Complex Links

As shown by Figure 8, among the links between components, we distinguish *simple links* and *complex links*. If C and C' are components admitting lower levels decompositions P and P' respectively, a (P, P')-*simple link** from C to C' binds together a *cluster** of links between components of P and P'. This just translates, at the level of C and C', information already contained at the levels of their components.

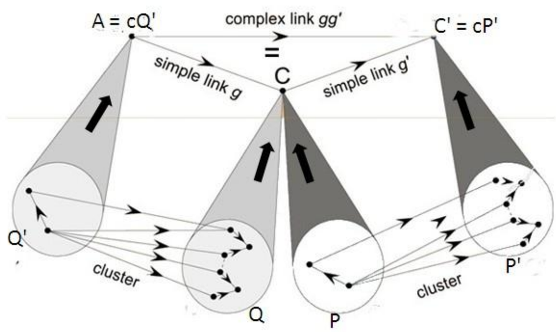

Figure 8: Simple and complex links.
C is a multifaceted component. The (P, P')-simple link *g'* binds a cluster of links between components of P and P'. Idem for the (Q', Q)-simple link *g*. Their composite *gg'* is a complex link from A to C'.

A main consequence of the Multiplicity Principle is the existence of another kind of links, named *complex links**. Let C be a multifaceted component of level *n*+1, with two structurally different lower levels decompositions, say P and Q; then, there are *n-complex links** from A to C' obtained as the composite of a (Q', Q)-simple link with a (P, P')-simple link (cf. Figure 8). Such a link does not bind links between components of A and C', but emerges at the level *n*+1 from the global structure of the lower levels.

Complexification and Emergence

The evolution of the design system, namely the successive transformations of its components and links between them, is essentially due to the formation of new components by combination of existing patterns of interacting components, and the suppression or decomposition of some existing components. As shown by Figure 9, these operations are represented by the *complexification** process which constructs the new configuration of the design system after the realization of such operations, describing both its new components and its links between them, which can be simple links, but also complex links made possible by the existence of multifaceted components C.

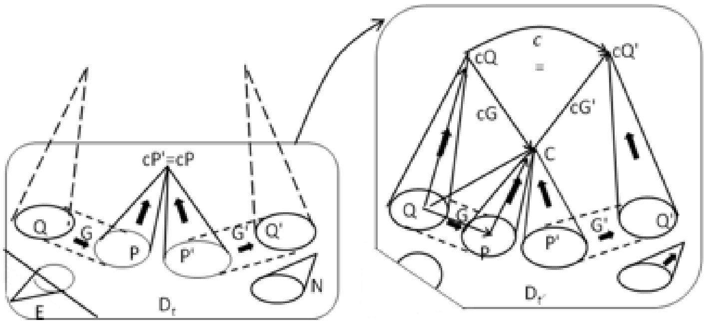

Figure 9: The complexification process.
The operations are: E is suppressed, Q and Q' acquire colimits cQ and cQ', the inductive cone N becomes a colimit-cone. The process then adds simple links cG and cG' binding the clusters G and G', as well as a complex link *c* composing these two links.

Fruitfulness of a Design System

In a D-MES, novelty occurs through successive complexification processes which, thanks to the Multiplicity Principle, render the emergence of complex links possible, which cannot be locally deduced from lower levels. In addition, it has been proved (Emergence Theorem*, A. C. Ehresmann and Vanbremeersch 1996) that the Multiplicity Principle allows the emergence of multifaceted objects of increasing complexity orders, so that they have long and unconnected ramifications; and these objects can have a high level of connectivity at the global level.

The fruitfulness of a design system will thus depend on:

- Its "*vertical complexity*": the increasing complexity orders of its components which ensure ramifications of increasing lengths (*e.g.* mental objects of higher abstraction, generic design strategies).
- Its "*horizontal complexity*": the number of unconnected decompositions and ramifications (*e.g.* multiple interpretations, polysemies).
- Its "*archetypal core*" (see next section): the formation of a rich and flexible internal model consisting of strongly connected higher components of the memory (*e.g.* shared knowledge, shared evocations).

Design Memory

In this paper, we define the *design memory* as an evolutive subsystem of D which is enriched whenever a new experience is conducted in the design system (individually or collectively). We then formalize how the interactions of all the designers acting as co-regulators can help developing a higher integrative part of the memory named the "archetypal core," which will play an important role in shaping their collective actions.

Co-regulators of a Design System

The dynamics of a design system D is modulated by the cooperation or competition of an evolving net of subsystems (*e.g.* designers, teams of designers...) which act as co-regulators and must co-exist and globally synchronize their action, although operating with different logics and discrete timescales. A *co-regulator* (CR) is an evolutive subsystem, namely an evolving pattern of components, called its *agents*, and links between them through which they can communicate. A component of the system can be an agent of several co-regulators; for instance, a designer can be a member of several design teams.

While the net of co-regulators does not form a strict hierarchy, but rather what has been named a "heterarchy" (Crumley 1995), co-regulators of different levels of complexity are distinguished, depending on the level of complexity of their components. For instance, within the design system, a design team can be represented by its own co-regulator CR' which has the interacting designers belonging to this team as components; CR' is of a higher level than the co-regulators representing its individual designers. Co-regulators can thus encompass a wide spectrum of entities intervening in the design process ranging from design tools and computers, to individuals, design teams, or institutions.

Structure and Dynamics of the Design Memory

The interactions of the co-regulators depend on the global memory of the system, which they also help developing over time through their interactions. As its components may be multifaceted, the design memory is simultaneously flexible, robust and adaptive for dealing with external changes. Each co-regulator has only a *partial access* to the memory.

The components of the memory are called *records*. They can be multifaceted with multiple decompositions and ramifications, and they evolve over time. A record can be stored or recalled (*i.e.* be activated) by another component of D, consciously or automatically. When two records are often activated together via the same link, then the strength of this link increases (this can be compared to Hebb's rule in the neural system, see Hebb 1949). Among the broad range of records stored in the memory, concepts, procepts and affects are of great importance in design.

Concepts are components which are, or name, abstract representations of an object, a situation, or an idea. They form the "semantic memory" of D and can be developed by logical processes (disjunction, conjunction, negation), by deduction (formation of chains of links, as in mathematical proofs), or by inference of any sort, in particular abduction (Peirce 1974 (1903)). *Procepts* are components enabling co-regulators to operate on the system. A procept is a "concept of a process" (Gray and Tall 1994). It can be associated with specific co-regulators (effectors) through which it can be realized in D. Procepts form the "procedural memory." As for any record, an important way to construct more complex procepts is to combine pre-existing ones. This may for instance lead to ever more generic design strategies for a group of designers. In particular, a procept can represent the changes to be done by a complexification process. Finally, note that the memory of the design system also includes percepts and affects, the latter playing an important role in the development of the archetypal core.

Archetypal Core

The *archetypal core* AC is a higher subsystem of the global memory (its emergence over time results from the *Emergence Theorem**). It is composed with highly connected higher order records, named *archetypal objects*, integrating knowledge and memories of different modalities, including emotions and unconscious evocations. These objects are often recalled so that their links become stronger and more permanent, forming *archetypal loops* which diffuse their activation in AC and preserve it for a long time. AC is developed through the interactions of various higher co-regulators which form new patterns of higher order components, progressively leading to the emergence, over time, of new multifaceted archetypal objects.

AC plays a central role in the design process and the interactions between the co-regulators. For instance, when two designers communicate on a new prototype they of course do not share the "same" visual or haptic perception of the prototype, but the information they exchange about it during the discussion allows the designers to enrich their own perception and collectively construct a more complete representation of the "same" prototype.

The Design Archetypal Pattern

During a design process, the archetypal objects and the specific links between them which intervene in this process form an increasing pattern AO of interconnected archetypal objects. The objects A of AO can be shared between components, say designers, acting together: initially a designer only perceives some ramifications of A; through exchanges with another designer who perceives other ramifications, he learns to also perceive these ramifications.

For instance, heterogeneous designers working on "new space devices for monitoring forests" may start with a very different understanding of what a "forest" is, whether they are engineering designers, space scientists or forests scientists. Through their interactions, they may all acquire an enriched meaning of the archetypal object "forest," which will become a shared mental object, while preserving distinctive internal resonances for each designer (cf. multifaceted objects). In the next section, we describe how this renders the formation of successive "macro-landscapes" possible.

Design Activities

In a D-MES, we define design activities as the sets of operations that are carried out by all the specific co-regulators which intervene in a specific design process, be they human or non-human. We distinguish between the local operative dynamics, which are developed by one single co-regulator CR (*e.g.* a designer in a design team or a team in a multi-teams project), and the global dynamics, which results from the interactions of the different co-regulators intervening in the design process. While some co-regulators might play an important role in the design process, our approach does not assume that there is a central control, but relies on an interplay between the various interacting co-regulators.

Local Operative Dynamics and "Landscape" of a Design Co-Regulator

As for the local design activities, we define the local operative dynamics as resulting from the operations that a design co-regulator CR carries out. CR operates stepwise according to its own time scale which defines its "specious present" in William James' terminology (James 1890). To do so, CR has a differential partial access to the global system memory which, in particular, allows its agents to recall its *admissible procepts*. Once again, note that part of this knowledge is unconscious or inaccessible. Each step of CR consists in successive phases which relate to what has been described under various labels, for instance: "situation analysis," "idea generation," "implementation," "evaluation" and "memorization." As these labels generally describe the creative work of humans only, we will rather use the general MES terminology and, for instance, conceptualize "mental spaces," which hold for humans only, as *local landscapes** which hold for all co-regulators (see Figure 10).

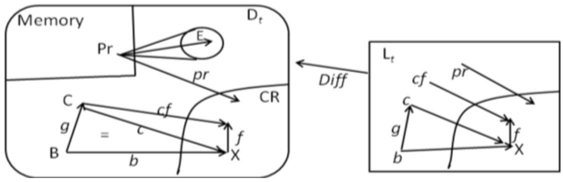

Figure 10: Landscape of a CR at *t*.
The link *b* in D_t activating an agent X of CR becomes an object *b* in the landscape L_t of CR

Thus in D one step of the co-regulator CR, say beginning at *t'*, divides in four successive overlapping phases:

i. *collecting information* to form the local landscape L_t of CR at *t*. It is a category whose objects are the links *b* from a component B of D to an agent X of CR which transmit information during the step (cf. Figure 10);
ii. *searching* an *admissible strategy* to cope with the situation; it is done by a search of an admissible procept in the memory accessible in the landscape;
iii. *activating the selected procept* Pr by sending its commands to effectors; formally it starts a complexification process through the landscape;
iv. *evaluating and memorizing the results*: the expected landscape after complexification is compared to the new landscape at the end of the step.

Figure 11 illustrates how CR selects a procept Pr in the memory. This procept Pr is “seen” as *pr* in its landscape L_t and allows CR to activate a pattern of effectors E via the link *e*.

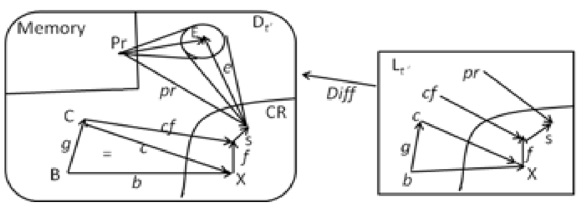

Figure 11: Selecting a procept and commanding its effectors. Selecting *pr* in L_t and sending commands to its effectors E via the activator link *e*

Global Dynamics of the Design System

Whereas the various co-regulators operate through their own local landscapes, their strategies and commands of effectors have to be implemented at the level of the global system. Conflicting situations may then occur because of the multiple individual views and actions during the “same” design process. In other words, there is a need for a global dynamic modulation to harmonize the various individual and local strategies and obtain a global action. However, let us note that this *interplay* among the co-regulators may cause problems to some of them, by not respecting their commands to effectors.

Formation of "Macro-Landscapes” in a Design System

In Section 3.4, we have explained how design coregulators working on a design process can construct a common archetypal pattern AO by sharing different ramifications of objects A of AO. The activation of AO diffuses to lower levels through ramifications and it persists for a long time thanks to the self-activation of archetypal loops. Therefore, it facilitates the recall of records of any level – through the unfolding of ramifications and switches between them – and keeps them activated for a longer time. The activation of the archetypal pattern AO may then lead to the construction of a *macro-landscape* D-Map, which unites and extends the local landscapes of the various higher co-regulators intervening in the design process (cf. Figure 15 which corresponds to a particular case). The extension is both temporal, thanks to the persisting self-activation of the archetypal pattern AO, and structural, due to its diffusion through ramifications toward lower levels of complexity, including non-conscious ones. D-Map is not the landscape of any co-regulator, but a macro-structure, extending and uniting all the local landscapes, in which the basic operations underlying collective design processes are carried out.

Retrospection, Prospection and Complexification in a Design System

D-Map makes it possible to collectively perform global analogs of the aforementioned phases for one single co-regulator. These basic collective design operations are: *retrospection*, *prospection* and *complexification* (and its evaluation).

Retrospection defines the operations which collect information about present and past objects, events and processes to collectively make sense of the situation. It consists in the formation of the macro-landscape D-Map and its analysis by deduction or abduction.

Prospection defines the operations led in a macro-landscape which enable the design co-regulators to collectively imagine various procedures Pr_i to cope with the design problem; they can consist in the formation of unknown objects by creative combinations of objects and processes of different complexity orders. Then these procedures are tested by construction of the corresponding complexifications in the macro-landscape. Prospection and retrospection are not carried out in the "same" macro-landscape, but over several successive overlapping macro-landscapes.

Complexification defines the operations through which the procedures Pr_i considered during the prospection can be realized in D. As the co-regulators cannot control all the effects of their local actions, nor necessarily perceive all of them, it is important to distinguish the "expected" results of a complexification constructed in the macro-landscape and the "real" effects that this complexification will have when realized on the system D.

Truly innovative design implies a recursive process of overlapping phases of retrospection, prospection and complexification leading to *successive complexifications*. The reason is that a single complexification introduces complex links between new multifaceted components (thanks to the Multiplicity Principle). When these new complex links emerge in the following macro-landscapes, they can play a major role in subsequent complexifications (cf. the Iterated Complexification Theorem*) by modifying the initial design rules. In Boden's terminology, an iterated complexification can lead to "transformational creativity," which differs from "combinatory" and "exploratory" creativities (Boden 2004). Because transformational creativity leads to reconfigure the internal organization of D and integrate new rules, it necessitates time to be integrated, which also accounts for the fact that, in practice, a period of incubation in the design process is often, if not always, necessary.

The next section illustrates these basic structures (archetypal core, archetypal pattern, and macro-landscape) and operations (retrospection, prospection, and complexification) in the case of garden design. The illustration is based on a five-year long collaborative research work carried out by the first author within a garden design agency. Results from this research have been published elsewhere (Béjean 2008) and, in the following, we only highlight the empirical observations that are related to our research goals.

Illustration

Like other design disciplines, garden design is composed of several design stages starting from client needs expression to site survey, conceptual design, planning and implementation. In the studied agency, a typical design project thus often started with clients expressing desired proprieties about plants or shrubs, especially in terms of colors and forms, often resulting in the designating of a specific botanic variety (e.g. "We love roses"). The clients then often asked technical questions about sun exposition or soil requirements regarding the aforementioned plants.

During this phase, the designers listened to the client, answered the technical questions but progressively also interrogated the clients more generally about the desired proprieties. In particular, designers started asking questions about the signification of these proprieties for the clients which they translated by formulating a provisory interpretation, for instance: "in fact, you're looking for liveliness." Based on this reformulation, the clients reacted differently as "liveliness" did not directly match with their own understanding of flowerbeds or mixed borders. Then the designers brought the clients to a place in which they had a collection of rare plants and started to sensitize them to new aspects of garden design, including textures, effects of lights or sounds.

Over time, a significant change in the way clients spoke of their garden project occurred. For instance, while often ignoring these aspects at the beginning of the project, they started making new formulations on textures with an increasing level of complexity. Such evolution made it possible for many of them to take part in the conceptual, the planning and the implementation phases of their garden design project.

To conceptualize and describe the design system of this illustration, here we only consider two co-regulators: the clients C and the design agency G, and their current environment, but other components could be integrated to the analysis. To do so, we characterize the operations that enable clients and designers to operate collectively by developing a design archetypal pattern AO and forming a macro-landscape D-Map where new compositions (or decompositions) of abstract or concrete objects and strategies will be imagined and considered. In the following, we illustrate how we model these collective and creative aspects of the considered design process, including emotions and inaccessible processes.

As shown by Figure 12, before the encounter, there is no *design archetypal pattern* AO. However, C and G have partial access to some connected objects of AC through active links *alpha* and *beta*. This means that they share a minimal piece of knowledge about gardens. On the figure, arrows represent active links and broken arrows represent existing but inactive links.

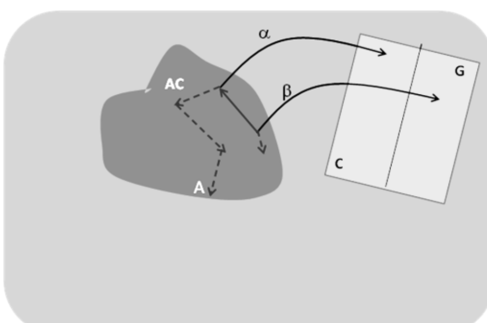

Figure 12: Before the encounter.

At a time t, the interactions between C and G about the garden project raise their attention, which is represented here by the formation of the *design archetypal pattern* AO and the activation of new links between its objects (see Figure 13). The links *f* and *g* between objects (agents) of the patterns (co-regulators) C and G represent the exchanges of information between C and G.

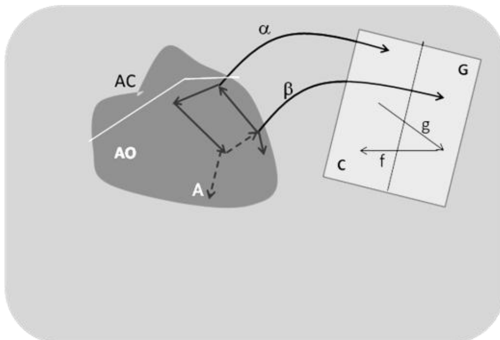

Figure 13: Formation of the design archetypal pattern AO.

Thanks to self-maintained *archetypal loops*, the activation diffuses within AO (activation of broken arrows of the previous figure) which unfold ramifications of an object A, for instance representing evocations associated to the concept of "garden." On Figure 14, whereas C initially only perceives decompositions associated to the pattern Q in its landscape via the link *v* (enabling it to express initial needs to G via the link *g*), G also has access to the pattern P via the link *u* (complex switch), for instance representing knowledge on how to provoke effects of "liveliness" in a garden. This interaction renders it possible for C to access to P via the new link *uf*.

Let us note that such evocations are not "controlled" as such, but emerge from the interplay of C and G. Likewise, the ramification of the object A may diffuse to lower levels that are not "consciously" accessible to C and G, while strongly influencing their collective design work.

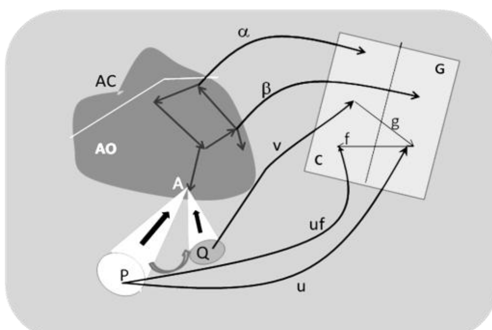

Figure 14: Activation propagated by AO (conscious and non-conscious evocations).

C and G keep on interacting and further exchange knowledge (both conscious and non-conscious) through active links *v* and *u* from ramifications of AO. As shown by Figure 15, these links are objects of a category D-Map which represents the macro-landscape of C and G at this time (*e.g.* the links *u*, *v*, *w* on the left diagram representing the system D become the objects u, v, w on the right diagram representing D-Map).

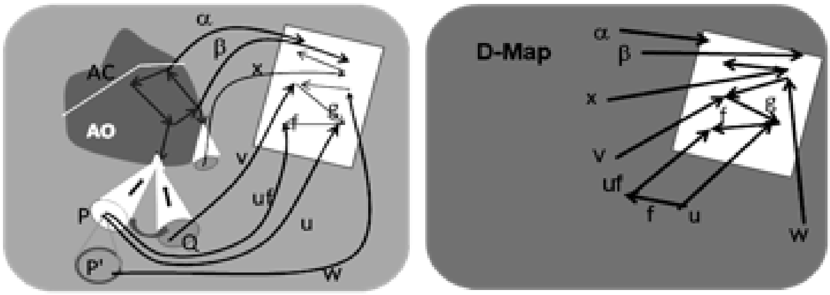

Figure 15: Formation of D-Map.

As archetypal loops of AO are self-maintained, D-Map persists during the entire design step. In addition, as shown on Figure 15, D-Map makes it possible to unfold ramifications of lower levels, (here associated to the pattern P') for instance representing evocations associated to garden textures. This allows G to sensitize C to these aspects and to open new ways in which to collectively explore the garden project of the clients.

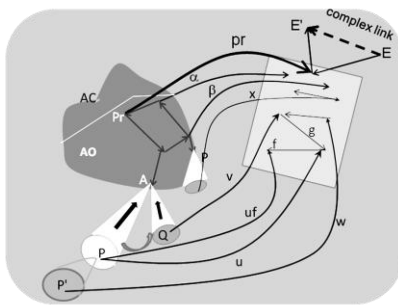

Figure 16: Formation of complex links.

As illustrated by Figure 16, the collective work then consists in searching for possible archetypal procepts Pr in AO, for instance related to the scenographic practices of G (including textural effects for creating "liveliness"). Here Pr is perceived in the macro-landscape through the link *pr*.

After testing these procepts on the system D via effectors (complexification process), new objects E and E' may appear, possibly leading to the emergence of complex links (as illustrated by the single broken arrow between E and E' on the figure)

Such complex links, when perceived in subsequent macro-landscapes, may be used to explore truly innovative design solutions via iterated complexifications.

Conclusions and Further Research

Based on the MES methodology, this paper develops D-MES an integrative mathematical approach to collective design processes. In line with previous research in design studies, it considers "design situation" and "design activities" as key generic concepts to a design system and provides formal definitions. Moreover, it also considers the internal dynamic of the design system and formalizes how its inner transformations are internally directed at each moment – instead of reconstructing them *ex post*; at this end, a third generic concept, "design memory," is integrated to the framework and accounts for how various entities can contribute to modulating the global dynamic of the design system (see Figure 17).

More specifically, the paper introduces the notion of archetypal core (AC), which represents a higher subsystem of the design memory, composed of higher order components, with many strong connections between them, as well as several decompositions and ramifications down to the lowest levels with possibility of switches between them providing flexibility. AC integrates memories of different modalities, including percepts, concepts, procepts and affects. In a design situation, the cooperating designers will be able to activate and share an archetypal pattern AO. Thanks to archetypal loops, which self-maintain their activity over a certain period, AO renders the formation of successive long term macro-landscapes D-Map possible, uniting and extending both temporally and structurally the local landscapes of the designers. In D-Map, higher collective design operations can be developed, namely: retrospection (making sense of the situation), prospection (constructing and testing design strategies) and complexification (realizing chosen design strategies). As a whole, AC plays a central role in collective design processes and explains how designers can cooperate on both conscious and non-conscious levels, the latter being of paramount importance in innovative design processes.

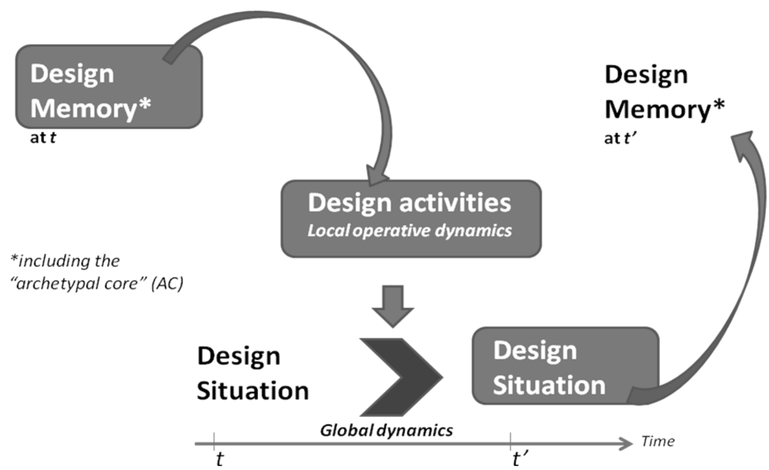

Figure 17: Summary

By formalizing the *becoming-at-work* of a design system, D-MES provides a general framework which integrates the creative, collective, cognitive and emotional aspects of design. As such, it extends prior research on collective design processes and contributes to design theory. In the future, this theoretical framework could be either used in educative or professional contexts. For instance, attempts to develop practices based on principles derived from D-MES are currently carried out at ENSCI Les Ateliers (Paris Design Institute) during "innovation by design" workshops bringing together engineers, managers and industrial designers. While still being work-in-progress, it indicates valuable directions for further research and potential ways in which to better assess the contribution of D-MES to innovative design practices.

Acknowledgement

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APPENDIX

Mathematical Notions

1. A *graph* G (also called a directed graph or a diagram scheme) consists of a set of objects, called its *vertices* (or nodes), which we denote by |G|, and a set of (directed) *edges* (or *arrows*) from a vertex A to a vertex B, denoted by *f*: A→B. We call A the *source* of the arrow, and B its *target* (Fig.1).
2. A *category* is a directed graph K equipped with an internal (partial) composition which maps a path (*f*, *g*) from A to B on an arrow *fg* from A to B; it is associative and each object has an identity; a vertex is called *object*, and an edge *morphism* (or '*link*'). *A functor* F from K to a category K' maps an object A of K to an object FA of K', a link *f*: A → B on a link F(*f*): FA → FB, and preserves the composition (Fig. 1).
3. A *pattern* (or diagram) P in a category K consists in a family o*f obje*cts $(P_i)_i$ and distinguished *link*s between them (in K). A *collective link* (or inductive cone) from P to C is a family $(s_i: P_i \to C)_i$ of links of K well correlated by the distinguished links *f*: $P_i \to P_j$ de P so that we have $s_i = fs_j$.
4. P admits a *colimit* cP in K if there is a collective link from P to cP through which any other collective link from P to an object C factors uniquely (Fig.3).
5. K is a *hierarchical category* if the class of its objects is partitioned into a finite number of complexity levels 0, 1, 2, etc, so that an object C of level n+1 is the colimit of at least one pattern P with each P_i of level < n+1. Then C also admits at least one *ramification* obtained by taking a lower level decomposition P of C, then such a decomposition of each P_i and so on down to level 0. The *complexity order* of C is the smallest length of one of its ramifications (Fig. 4).
6. An *Evolutive System* (ES) **K** is a family $(K_t)_t$ of categories and partial 'transition' functors between them satisfying a transitivity condition; a *component* of the system is a maximal family of objects of the K_t related by transitions. (Figure 2.) **K** is a *Hierarchical Evolutive System* (HES) if the categories K_t are hierarchical and the transitions respect the level (Fig.4).
7. A component C of the HES **K** is *multifaceted* if it admits at least two lower level decompositions which are not isomorphic nor connected by a cluster (= well-correlated family of links between their components). **K** satisfies the *Multiplicity Principle* if **K** admits such multifaceted components. In this case besides *simple links* from A to C which bind clusters of links between decompositions Q of A and P of C, there are *complex links* obtained by composing simple links binding non adjacent clusters (Fig. 8).
8. *Complexification.* A *procedure* Pr on a category **K** consists of a subset E of **K**, a set I of inductive cones, a set D of patterns in **K**. The *complexification* of **K** for Pr is a solution of the universal problem of finding a category **K'** with a partial functor F from **K** to **K'** satisfying: F is defined on the largest sub-category of **K** not including E, it transforms the cones in I into colimit-cones in **K'**, and FQ for each Q in D, acquires a colimit cQ in **K'** (Fig. 9).
9. *Emergence Theorem*. The Multiplicity Principle is necessary for the existence of components of complexity order > 1. It allows the emergence of components of increasing complexity order through successive complexifications.
10. The *landscape of a co-regulator* CR at time *t* is the category L_t whose objects are links from a component to CR which are active during the step beginning at *t* (Fig. 10).
11. *Iterated Complexification Theorem.* Two successive complexifications of a category satisfying the Multiplicity Principle cannot be reduced to a unique complexification (the

proof relies on the role played by the complex links emerging in the first complexification).

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