Design and Validation of Dynamic Hierarchies and Adaptive Layouts Using Spatial Graph Grammars

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1. Introduction

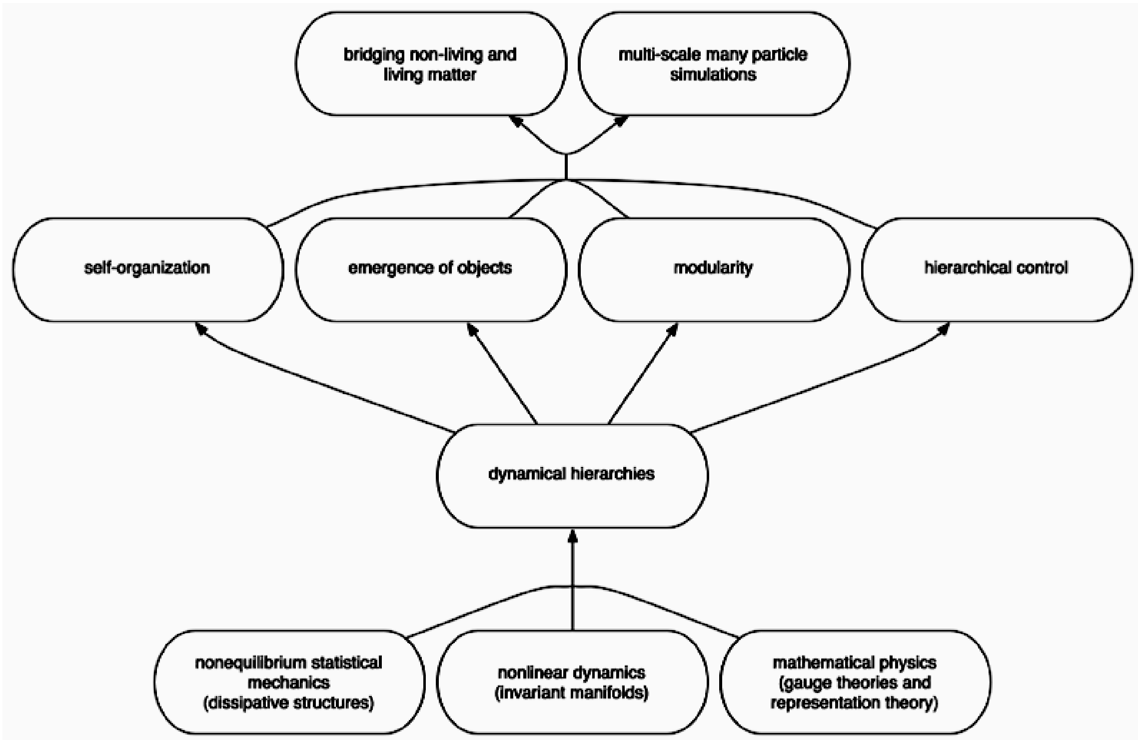
The paradigm of pattern-based design has being widely adopted in the fields of software engineering (Gamma et al. 1994, Zhao et al. 2007a, 2007b), spatial information representation and reasoning (Kong and Zhang 2003) and data mining (Qian et al. 2004). The idea "design patterns" rooted in Chomsky's "Generative Grammar" and formal language theory (1956, 1957), Simon's "Hierarchy and Complexity" (1962, 1973) and Fu's "Pattern Grammars" (1971, 1976), etc. These original and visionary works shed light on the research of theories and methodologies on "patterns" and "pattern-based design" with complexity theories, especially information theory of complex systems (Lindgren K 1988, 2003). However, in environmental planning and design, formal pattern-based design methodologies are still absent, although there are notable early explorations (Stiny 1972, Yessios C 1972, 1987, Alexander 1977). This paper proposes a formalized framework of the process and mechanics of pattern formation, in the context of physical planning and architectural design for 2D space layout. It discusses parsing and generation of such layout, on the basis of complex systems and the related information theory, design cognition and knowledge representation (Vries et al. 2010).

2. Theory and Methodology

First of all, it is significant to re-interpret our understanding of pattern and pattern formation with a shift of thinking paradigm on the evolution of complex adaptive systems. This presents us a profound notion that pattern is actually a fluctuating one driven by system dynamics (Prigogine 1977, Liao 1997, Liao and Li 1997).

2.1 Dynamic Hierarchies with Emergence

Simon considered hierarchy to be primary to understand "the organization of complexity", and pointed out "any complex system in the world must be hierarchical, or otherwise we would have no way to acquire it" (1962, 1973). Holland presented his theory of "Emergence" in 1998. In contrast to Simon's structuralism perspective, Holland regards that the process of emergence is crucial, and hierarchical organization is a consequence of this process. Many higher-level "entities" are patterns of organization rather than stable aggregates of lower-level entities.



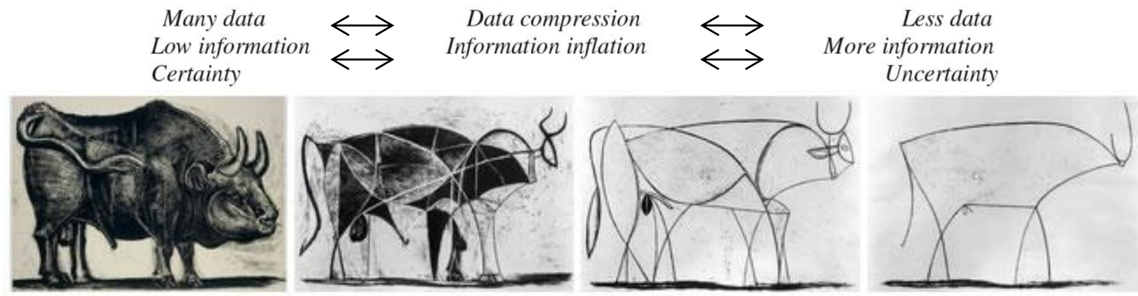
(Source from the Project EMBIO "Emergent organisation in complex biomolecular systems" Meeting at Cambridge University in July 2005)

Figure 1. An overview conceptual framework to model the evolving of complex adaptive systems (in case of physical-biomolecular systems)

Referring to Figure 1, and Holland's theory "hierarchical organization that emerges in Emergence", with emphasis on bottom up "building block interactions" and "persistent patterns" with "perpetual novelty" (Holland 1995, 1998, Lane 2006), we consider complex systems as dual organization phenomena determined by both of structural and process constraints. Thus, we would understand dynamic hierarchies act as the key role of the process and mechanics of pattern formation with emergence.

2.2 Modeling with Multiple Representations

In complex and open systems, the organizational structure and spatial information of patterns would be emergent, along with the phase transitions between equilibrium states, together with the re-distribution of their related structural information. Pattern formations are critical phenomena during complex systems evolving, with spatial information processing (interaction and adaptation). To model "Evolving Hierarchical Systems" (Salthe 1985), we should not only understand their structures, but also model and represent the process (both "upward causation" and "downward causation") across multi-level hierarchies.



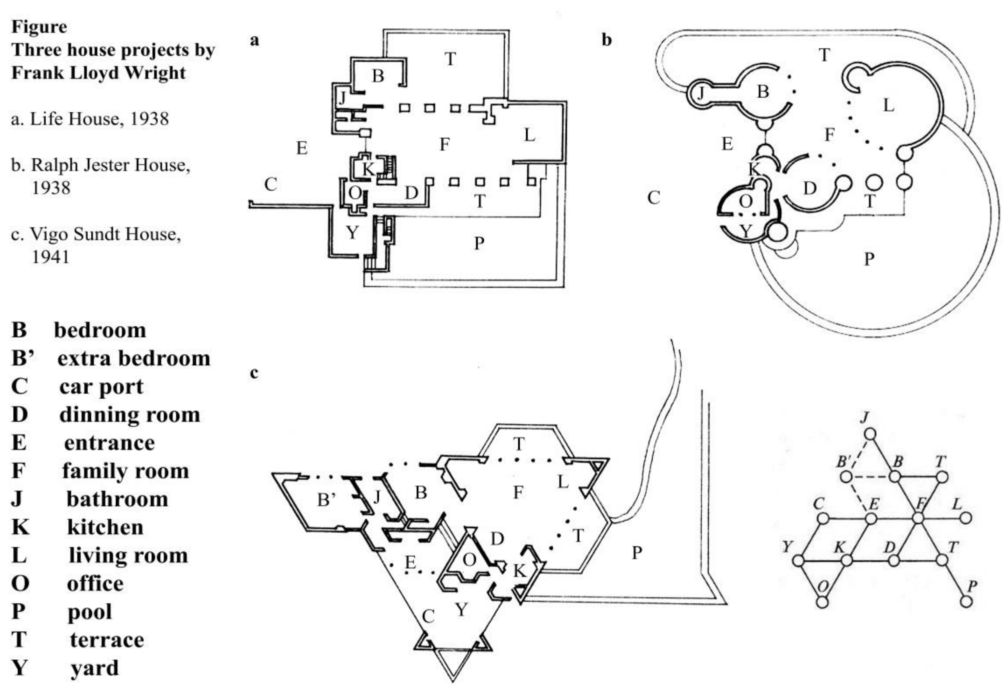
(Source from Haken H and Portugali J 2014)

Figure 2. An illustration of spatial information processing across multiple cognitive levels within multiple design representations

Therefore, our study is focused on the modeling on spatial information processing during design process across the different design cognition-level hierarchies (either at intra-level or/and at inter-level). It serves the process and mechanics of pattern formation, with multiple design cognition and knowledge representations (Liao et al. 2015) (Figure 2).

2.3 Adapting to Layout Context with Spatial-Semantics

Having spatial information processing with multiple design knowledge representations, the spatial decisions of planning and design should correspondently across the dynamic hierarchies of scales/levels knit together. This would form desired patterning and order, by interacting with and adapting to the situational and environmental context.



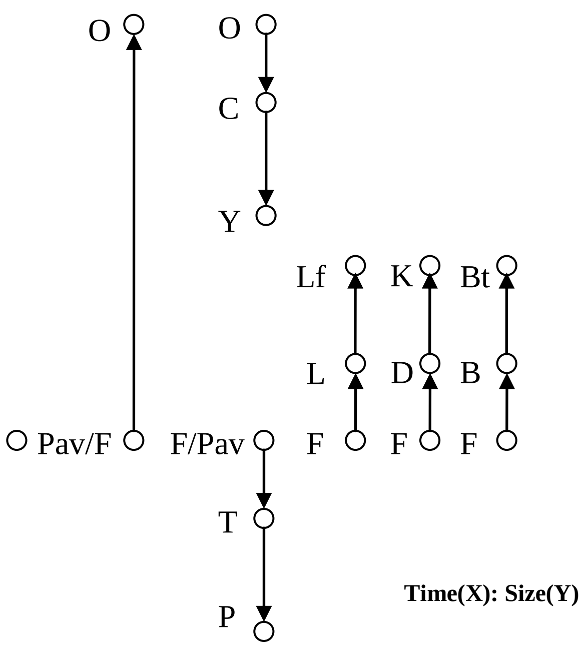
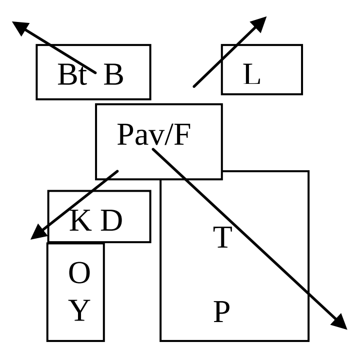
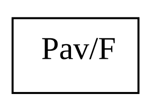
(Source from March and Steadman 1974)

Figure 3. Three house projects by Frank Lloyd Wright with spatial topological similarity

However, for the existing design representation models and computational tools, there is a cognitive gap between low-level spatial data/information and high-level design knowledge. The relevant formal studies (especially on the architecture-specific, design-oriented formal spatial representation and reasoning, ontologies and spatial semantics) are limited (Egenhofer M 2015). This deficiency prevents a direct cross-link between spatial-coordinate information and generic knowledge representation during the design process. To bridge the gap, our model aims to integrate topological, metric, and semantic features of 2D space layout design within a unified framework, for design-pattern mining, retrieval, (re-)configuration, generation and translation. An approach of Spatial-Semantics for dynamic hierarchies and adaptive layouts design is proposed.

3. Implementation

The architectural layout of above three house projects by Frank Lloyd Wright is selected as our case studies. We suggest that a Pivotal Pavilion (locates at “F”, the family room area for each) acts as the circulation nexus, social communication hub and the visual/compositional crux of the layout design. Respectively, the floor plan of Figure 3(a) includes Rectangle, (b) includes Square, and (c) is Hexagon, as shown above (Figure 3).

Event Listing of Production during the Compositional Processing	**Spatial-Semantic Analytics,** including Cardinal Direction Relations, etc.
	 **Cardinal Direction Relations** **x Size** **x Balance & Alignment**
Level I (Initial state) (0) The Pivotal Pavilion = F; (1) F (family room) < Fig. 14(a)-Rectangle, 14(b)-Square, 14(c)-Hexagon>	

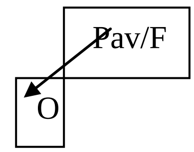
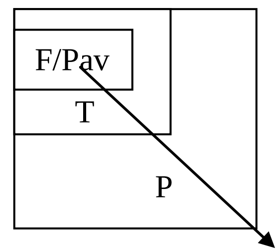
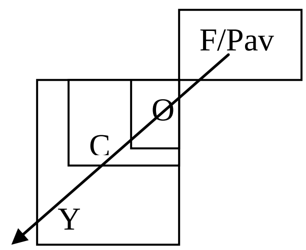
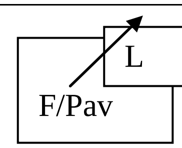
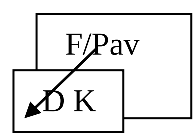
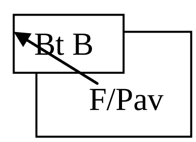
Level II (Start state) (2) F-O (family room to office) - O (office), the Minor Pavilion, at the south-western corner of the Pivotal Pavilion (2.1)The Office < Fig. 14(a)-Rectangle with 90 degree rotation, 14(b)-Square, 14(c)-Hexagon>	
Level III (Continue state) (3.1) (E)-((F)-T)-P (the large block of F-T-P with "the Grand Courtyard") (grand courtyard) := (Entrance - family room – terrace – pool) Level III (Continue state) (3.2) (C)-((F)-O)-Y (the small block of F-O-Y with "the Tiny Courtyard") (tiny courtyard) := (office-carport - yard)	 
Level IV (Continue state) (4.1) (F)-L-Lf: family room to living room, then to fireplace	
Level V (End state) (5.1) (F)-D-K: family room to dining area (D/dining room, K/kitchen, corridor, etc.) (5.2) (F)-B-Bt: family room to bedroom area (B/bedroom, Bt/bathroom, corridor, etc.)	 

Table 1. An illustration of the graph grammar and Spatial-Semantic Analytic Maps for three house projects by FL Wright (see Figure 3).

Setting up the Pivotal Pavilion (Pav/F) as the origin of coordination system and the start point of spatial layout, we conduct "Parsing" operation with the Spatial-Semantic Analytics on the layout design, so as to generate the graph grammar and Spatial-Semantic Analytic Maps (Table 1).

A Spatial Graph Grammar (SGG) specification, parsing and induction tool, called *VEGGIE* (*a Visual Environment of Graph Grammar Induction Engineering*) developed by Zhang and Kong (Kong et al. 2006, Zhang 2007, Ates and Zhang 2007) is employed for the experimental design.

4. Conclusion and Discussion

Through "Parsing" with *VEGGIE*, we would be able to represent, retrieve and re-generate design patterns of 2D architectural spatial layouts automatically. Although our work is at a preliminary stage, we demonstrate the application potential of incorporating the novel computational approach of SGG (which is originally developed for the applications in software engineering, data mining and information visualization/visual analytics) into the conventional computation approaches in environmental planning and design. We will continue to develop our computational analysis model and design tool by using SGG.

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