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DESCRIBING THE ENGINEERING MODELING KNOWLEDGE FOR COMPLEXITY MANAGEMENT IN THE DESIGN OF COMPLEX CITY

Egon OSTROSI (1,2), Fabien PFAENDER (2,4), Denis CHOULIER (1), Alain-Jérôme FOUGÈRES (1,3), MonZen TZEN (2)
1: Université de Technologie de Belfort-Montbéliard, France; 2: University of Shanghai, China; 3: ESTA, France; 4: Université de Technologie de Compiègne, France

ABSTRACT
Engineering design and planning of the city of the future for its citizens of all ages with its fast and dynamic evolving structure is a complex problem. The goal of this paper is to propose a new model for describing engineering modeling knowledge using “what we want to achieve” and “how we want to achieve” relationships and transformations. This will help us to assist the complexity management in engineering design of the city of Shanghai considered as living laboratory. The proposed model is based on the principles of the axiomatic design approach, structured on four levels of modeling: (1) conceptual (2) mathematical (3) computational and (4) experimental. Our approach advocates that a complete engineering modeling framework is necessary for managing engineering design of a complex city. The model captures the knowledge of engineers through the building sixteen key models. It can be used for the development and the diagnostic of the engineering design process of a complex city. The paper presents some findings from the application of the proposed meta-model.

Keywords: complexity, design management, knowledge management, design methodology, experimental models

Contact:
Dr. Ing. Egon Ostrosi
Université de Technologie de Belfort-Montbéliard
Laboratoire IRTES-M3M
Belfort
90010
France
egon.ostrosi@utbm.fr

1 INTRODUCTION

Engineering design and planning of the city of the future for its citizens of all ages with its fast and dynamic evolving structure is a complex problem. This complexity results from the conjugation of a huge amount of heterogeneous data interacting with each other. Our first claim is that engineering design theories and practices can successfully be applied in the engineering design of complex city. The second claim is that modeling knowledge plays an important role for enhancing the rationality and usability of engineering models in the engineering design of complex city like Shanghai. Engineering design can be analyzed, synthesized and validated through dynamic engineering models. Developing models for describing the engineering modeling knowledge can improve the quality of complexity management in the practice of the engineering design of complex cities.

In the past, there were many attempts to draw up models to handle the complexity management of design process in systematic steps (French, 1971; Pahl and Beitz, 1984; Hubka and Eder, 1988; Suh, 1990; Albano and Suh, 1992). Both functional modeling and structural modeling have been investigated (Erens, 1997; Ulrich, 1995, Jiao and Tseng, 2000; Otto and Wood, 2001; Pahl and Beitz, 1984; Suh, 1990; Welch and Dixon, 1992). The goal of design engineering is the conversion of a perceived need or a technical problem into information from which a product can be built in sufficient quality and reasonable cost to meet the needs or to overcome the problem (Hales, 1992). Design process usually starts with the identification of a need, proceeds through a sequence of activities to seek for a solution to the problem, and ends with a detailed description of the product or the technical system.

This paper presents a model for describing the engineering modelling knowledge to assist the complexity management of the design of complex cities in light of a detailed understanding of "what we want to achieve" and "how we want to achieve" relationships and transformations. It is based on the principles of axiomatic design theory structured on different levels of modelling. Axiomatic design approach considers design as interplay between what we want to achieve and how we want to achieve it. Engineering design progress through interplay and iterations between "what we want to achieve", representing functional modelling, and "how we want to achieve", representing structural modelling.

This model can be applied to great advantage in the design of complex city. The proposed model can capture better the engineering modelling knowledge because it provides: (a) a disciplined way of thinking, (b) a disciplined way of modelling and (c) modelling tools and techniques.

The remainder of the paper is organized as follows: In the second section, the model for engineering modelling analysis is proposed. The third section describes the engineering models. The forth section proposes an application of the proposed model. In the last section, the conclusion shows the interest of the proposed approach.

2 PROPOSED META-MODEL FOR ENGINEERING MODELLING ANALYSIS

In this research, the city is considered and conceived as an evolving living product (body) in complex interaction with its citizens, its artificial physical environment, and its natural physical environment in a time. Indeed, the size of the evolution of a city is not only measured in terms of space but also in terms of time. Time is a determining marker. In addition, to systemize the engineering design knowledge for the design of a city, the concept of domains is used (Suh, 1990). The world of design modelling of a city as a living product can be defined in four domains: *citizen domain, functional domain, physical domain and process domain* (Figure 1).

The citizen domain is characterized by attributes a citizen desires. With this viewpoint, a city is seen for what it gives to the citizen, without or with very few knowledge on the life of the city or how the city, as a living product, works. For instance, a citizen does not necessarily know which type of energy is more comfortable and efficient. But he or she can describe the characteristics he or she wants considering its effects on the pollution of the city. The citizen domain includes attributes related to acoustics and noise, heat transfer and ventilation, daily and artificial light.

The functional domain specifies functional requirements. In the functional domain, desired performances are specified for the city as a living product. This domain refers to the actions and interactions that the city as a living product has with its environment during its life. These interactions are multiple, complex and dynamic. They define the behaviour and functions of the city. We consider that functions are abstractions of behaviour which is coherent with Yoshikawa's concern on the notion of abstraction (Yoshikawa, 1981).

To satisfy functional requirements, designers and engineers imagine and define design parameters in the physical domain. Design parameters are physical variables in physical domain. Physical components of the city, physical fields in the city and the structure of the city as a living product (metabolism) represent these design parameters. The structure of city is a strategic element in the development of renewable energies.
Finally, the process domain is characterized by process variables. Process variables describe the process developed to realize the city as a living product specified in terms of design parameters.

	Citizen domain	**Functional domain**	**Physical domain**	**Process domain**
Conceptual model	*Conceptual model of citizen domain*	*Conceptual model of functional domain*	*Conceptual model of physical domain*	*Conceptual model of process domain*
Mathematical model	*Mathematical model of citizen domain*	*Mathematical model of functional domain*	*Mathematical model of physical domain*	*Mathematical model of process domain*
Computational model	*Computational model of citizen domain*	*Computational model of functional domain*	*Computational model of physical domain*	*Computational model of process domain*
Experimental model	*Experimental model of citizen domain*	*Experimental model of functional domain*	*Experimental model of physical domain*	*Experimental model of process domain*

Figure 1. Matrix of engineering modelling analysis

Two cross-referencing modelling levels with four domains are proposed: 1) *Conceptual models* and 2) *Concrete models*. The later are decomposed into: *Mathematical model, Computational model and Experimental model* (Figure 1).
A *conceptual model* refers to designer's models which are represented by concepts or related concepts for city modelling. A conceptual model for city modelling is a model of designer's qualitative understanding and predictions of some knowledge of the city as a living product. A conceptual model can exist prior to building a mathematical model (Nomaguchi et al. 2010). It is formed after a conceptualization process and can be used for representing interplay and iterations between domains. Conceptual models offer flexible and adaptive tools for discussing and representing qualitatively designer intentions and semantics by using more formal languages. Conceptual models can also use natural language. They obey to semantic rules and are codified.
Concrete models give a fine and acute description of the knowledge for city modelling. Quite systematically, they used a formal description with a codified and specific language quite different from natural one. We can distinguish three subclasses of such models: (a) *mathematical models;* (b) *computational models* and (c) *experimental models*.
A mathematical model represents empirical objects, phenomena, and physical processes encountered during city modelling in a mathematical or logical way. Mathematical models can take many forms such as dynamical systems, statistical models, differential equations, game theoretic models, category theory or mathematical structures.
A computational model is the representation of a mathematical model in computational way. Like in engineering design, analytical solutions are not readily available for the design of complex city. Therefore, design engineers use computational models by computer simulation. When a computational model is available, experimentation with the model is possible by adjusting design parameters in the computer, and by studying the differences in the outcome of the simulation. Often, computational models are used as "*black boxes*" models.

An experimental model represents empirical objects, phenomena, and physical processes encountered during city modelling in an experimental way. It is concerned with the observation of phenomena, social and physical, in order to gather data about the design of the city. Experimentation can be done on the city itself or on a physical model representing part of its characteristics for accessing ad hoc interactions with the designer, with external actions or with the citizen. Even if experimental model tends to disappear, experimental models in city design offer the possibility to represent interactions that have not been modelled, and even not been identified. It has a wealth of discovering new problems and can build on considering the city as living laboratory.

In this paper, *engineering design of a complex city is seen as a process of building of engineering models from citizen domain to process behaviour domain*. Matrix of engineering modelling analysis (Figure 1) classifies 4 x 4 types of engineering models corresponding to the intersection of the four levels of modelling with the four engineering domains.

3 ENGINEERING MODELS IN PROPOSED MATRIX

This section describes 4 x 4 types of engineering models corresponding to the four levels of engineering in the intersection of four domains (Figure 1).

3.1 Conceptual models

Conceptual model of citizen domain. A conceptual model of citizen domain is a qualitative representation of citizen attributes or desired city characteristics. When using oral language, citizen requirements should be expressed with the citizen's own words such as "*very easy*", "*fast*", "*natural*" and other abstract terms (Ullman 1992). The language used shows that there is an uncertain determination of citizen attributes or desired city characteristics, the citizens relying on qualitative linguistic information. Nevertheless, a more formal language could be useful here. The notion of affordance developed by Maier and Fadel (2009) offers such a language if we restrict it to the citizen domain. An affordance, in the context of the design of a city, is the abstract expression of what a city, as a living product, offers to its citizens. As for functions, a codified language for expressing affordances could be developed in a form "*the city offers X to Y*"; where *X* is an ability/capability and *Y* the citizen.

Conceptual model of functional domain. A conceptual model of functional domain captures qualitatively the intended functionality of the city, as a living product. Conceptual model of functional model represents the desired functions of the city and theirs decompositions. There are many different interpretation of the notion of the function in engineering design (Chakrabarti and Blessing, 1996; Erden et al. 2008) which can be extended in the design of a city. Functions can be defined as the abstracted behaviour (Chandrasekaran and Josephson, 2000; Chandrasekaran 2005) of a city, considered as an artifact, that is intended by its citizens. Functions are described in terms of the logical flows of energy, material and signals. A verb-object language is used to define functions, as for instance: "*keep water off the road*". Subfunctions are also described by verb-object forms. They can correspond to well-defined basic operations on well-defined basic flows of materials, energies, and signals leading to a taxonomy of functions (Hirtz et al., 2002; Stone and Wood, 2000; McAdams et al. 2005). Functional architecture of a city is a form of conceptual model of functional domain. A conceptual model of functional domain is a qualitative representation of the physical behaviour of the physical structure of a city. The physical structure in interaction with a physical environment, gives rise to the citys' behaviour. For instance, *"the amount of heat to be dissipated per square metre in summer is on a par with the amount of heat required for heating in winter when high levels of thermal insulation are realized"* is a qualitative representation of behaviour of physical structure at a particular instant. Behaviours are related to structural-physical descriptions of the city. Behaviours come out in some way the citys' functions.

Conceptual model of physical domain. A conceptual model of physical domain is a qualitative representation of design principles and physical principles in design of a city. It represents structural-physical descriptions of the city. Rough drawings, drafts, schematic representations… can also be considered as conceptual representations of a physical structure providing they do not contribute to the fixation of the city description, leaving place for some interpretation. As for affordances and functions, conceptual models of physical domain obey to some semantic, for instance conventions used in drafts and diagrams. Conceptual physical models are often used for discussing possible options for solutions. Especially, the first goal in the conceptual phase is to find as many concepts as possible that can provide each function identified in conceptual model of functional domain. Since many models are currently necessary, they have to be "cheap" and easy to produce and transform. The second goal is to configure these individual concepts into an overall concept. The laws of TRIZ (Altshuller, 2002; Orloff, 2003, Choulier, 2011) can be used to determine the city structure satisfying its functions.

Conceptual model of process domain. A conceptual model of process domain is a qualitative representation of process variables that can control design parameters. As for the other conceptual models, the use of flexible languages such as verbal language and drawing is useful. But one can also use classes of processes not detailed such as the classification of processes.

3.2 Mathematical models

Mathematical model of citizen domain. A mathematical model of citizen domain is a formal representation of citizen attributes or desired performances of design. For instance, the definition of the linguistic values and their transformation into a degree of membership or a degree of belief is still an open question in the real world of design. It tolerates imprecision, which can be exploited to achieve tractability, robustness, low solution cost, and better rapport with reality (Zadeh, 1996).

Mathematical model of functional domain. A mathematical model of functional domain represents functions formally. A formal representation of functions is a prerequisite for representing functions in computers. A mathematical model of the behaviour represents formally the behaviour of the physical model. In engineering science, many models are available.

Mathematical model of physical domain. A mathematical model of physical domain is a formal representation of physical variables, design principles and physical principles in design of a city. For instance, for physical objects, the topology of a city can be described using formal representations.

Mathematical model of process domain. A mathematical model of process domain represents formally process variables and process physical principles.

3.3 Computational models

Computational model are based on grounded mathematical models. Computation is no more than a way to achieve results when mathematical solutions are difficult to obtain, either impossible or too long in the case of the design of a complex city. They can use some simplifications and approximations of mathematical models, for instance using a discrete model approaching a continuous one.

Computational model of citizen domain. Computational model of citizen domain represents citizen's requirements computationally. Computing with linguistic values is a necessity when the information is subjective, hence imprecise (Zadeh, 1996).

Computational model of functional domain. A computational model of functional domain represents functions computationally (Wood, 2009). It offers a solution of mathematical representation of functions.

Computational model of physical domain. A computational model of physical domain is a computational representation of the corresponding mathematical model. It is a computational representation of design principles and physical principles. A computational model of physical domain represents structural-physical descriptions of the city in computers. For instance, a CAD model is a computational model of the city.

Computational model of process domain. A computational model of process domain is a computational representation of process physical principles.

3.4 Experimental models

Experimental model of citizen domain. An experimental model of citizen domain is an experimental representation of attributes that citizens desire. The involvement of citizens in a design process is a way to obtain information, and experimental models can offset the lack of mathematical and computational models of citizen domain. Tests with effective citizens or representatives of them are necessary as soon as the acceptation or the differentiation of components of a body of a city as an evolving living product is a key feature for innovation. Feedbacks from effectively used components are also a means for capturing the information from the citizens.

Experimental model of functional domain. An experimental model of functional domain represents the behaviour of functions of a body of a city experimentally. The test in real or simulated conditions or tests of parts of a body of a city can be used. Feedbacks from effectively used can also give technical information in real conditions.

Experimental model of physical domain. An experimental model of physical domain is an experimental representation of design principles and physical principles encountered or applied in the design of the city. A physical mock-up is such a model. It can be manipulated by designers in order to have a concrete representation of the structure of the city.

Experimental model of process domain. An experimental model of process domain is an experimental representation of process physical principles applied in the building of the city.

4 APPLICATION – COMPLEX CITY OF SHANGHAI

This section describes the usability of proposed engineering models in the engineering design of complex city like Shanghai (Figure 2).

<table>
<tr><th colspan="2"></th><th>Citizen domain</th><th>Functional domain</th><th>Physical domain</th><th>Process domain</th></tr>
<tr><td colspan="2">Conceptual / abstract models</td><td>Abstract representation of the attributes citizen desire.</td><td>Functional requirements specified for the city.</td><td>Physical variables that can satisfy functional requirements. Qualitative representation of design principles and physical principles.</td><td>Abstract representation of process variables that can control design parameters.</td></tr>
<tr><td rowspan="3">Concrete models</td><td>Mathematical</td><td>Mathematical representation of attributes that citizens desire.</td><td>Representation of city behaviour: Mathematical representation of functions.</td><td>Mathematical representation of physical variables. Mathematical representation of design principles and physical principles.</td><td>Mathematical representation of process behaviour. Mathematical representation of process physical principles.</td></tr>
<tr><td>Computational</td><td>Computational representation of attributes that citizens desire.</td><td>Representation of city behaviour: Computational representation of functions.</td><td>Computational representation of design principles and physical principles.</td><td>Computational representation of process physical principles.</td></tr>
<tr><td>Experimental</td><td>Experimental representation of attributes that citizens desire.</td><td>Representation of city behaviour: Experimental representation of functions.</td><td>Experimental representation of design principles and physical principles.</td><td>Experimental representation of process physical principles.</td></tr>
</table>

Figure 2. Matrix of engineering modelling analysis

4.1 Developed models

Experimental model of citizen domain is the first model developed in this application. Understanding of "*what citizens want*", its progress and advancement can be achieved by observing the dynamics of interactions between different citizens in real time. Within engineering design of a complex city like Shanghai, large quantities of information and knowledge are widely distributed across citizens. Therefore, in this application, *it is assumed that Shanghai is a living laboratory*. This living source of

information on citizen interactions can allow design researchers to develop richer models of designing which in turn will provide the basis for a better understanding of engineering design problems of a complex city and developing intelligent tools to support this process. The goal of our research presented in this study, consists in discerning, from the real interactions, the different citizens' problems on one side, and the dynamics of citizen organizations to these problems on the other. In the frame of our research, the experiences with citizens are used as a situation of observation.
A first analysis carried out on the usage of microblogging Weibo by women and man showed that different patterns of behaviour were detected (Figure 3). It was found that women tend to use more frequently the microblogging Weibo than men and their distribution of the usage in the same area is different. The usage of the microblogging Weibo by men is concentrated in some area. Otherwise, the usage of Weibo by women is more distributed. Some remarkable overlapping of usage by two genders is also found. The switching from a pattern of behaviour to another by women and men is also interesting. This remarkable finding bears the gender issues in the design of microblogging service.
A second analysis of the interaction between the citizens and different objects considering the task of citizens and roles of these objects is also carried out (Figure 4).

Figure 3. Distribution of usage of microblogging: women versus men

The problem then consists in analyzing the real interactions between citizens without the influence of the observer. The attempt is to understand and interpret the interactions and their dynamics. Interactions acquire, manipulate, and create information through the joint, interlocked activities of different citizens and automated information technologies. During interactions, citizens communicate their thoughts verbally or in writing. Experiences show that the majority of real problems appear through verbalizations and writings. Therefore, the verbal and written communication offers us a direct path to the state of problems. For that reason, we consider a message as being a form of the representation of a problem. It can be characterized by a set of syntactic elements with a specific semantics to a domain of knowledge. The category of these elements is called analysis entities (Movahed-Khah et al. 2010).
Computational model of citizen domain and *Mathematical model of citizen domain* are used to study both citizen and automated organization as computational entities. Interactions have been viewed as inherently computational. Every interaction is filtered by means of analysis entities. Clustering the entities of analysis can be considered a principle for *state-problem* discovering. Clustering permits to identify families of analysis entities (Figure 4). Mathematically, the search for interaction families and analysis entities families is a problem of search for simultaneous partitions of the two sets, the filtered interactions set and analysis entities set in correspondences or in quasi-correspondences class of partition to class of partition. Hence, this correspondence permits to characterize an interaction family by the corresponding analysis entities family that is by the corresponding *state-problem of citizen*. If the families of state-problems are mutually exclusive, it is clear that the state-problems are completely independent. In practice, depending on the particular nature of the citizen problems, some or all of the state-problems result in either being mutually independent or not being as such. This means that interactions create "*state-problems within a state-problem*".

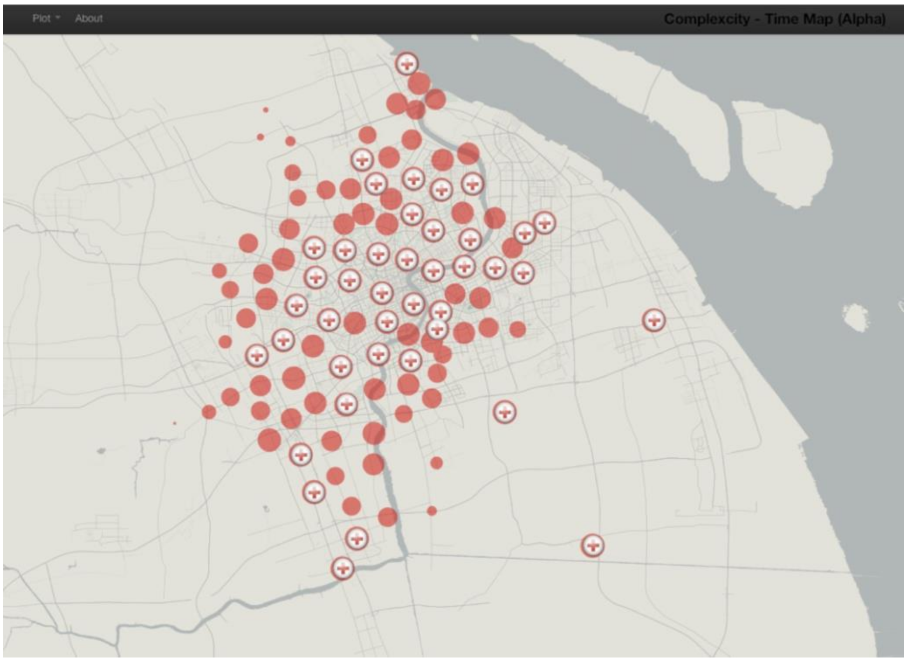

Figure 4. Real interactions between citizens

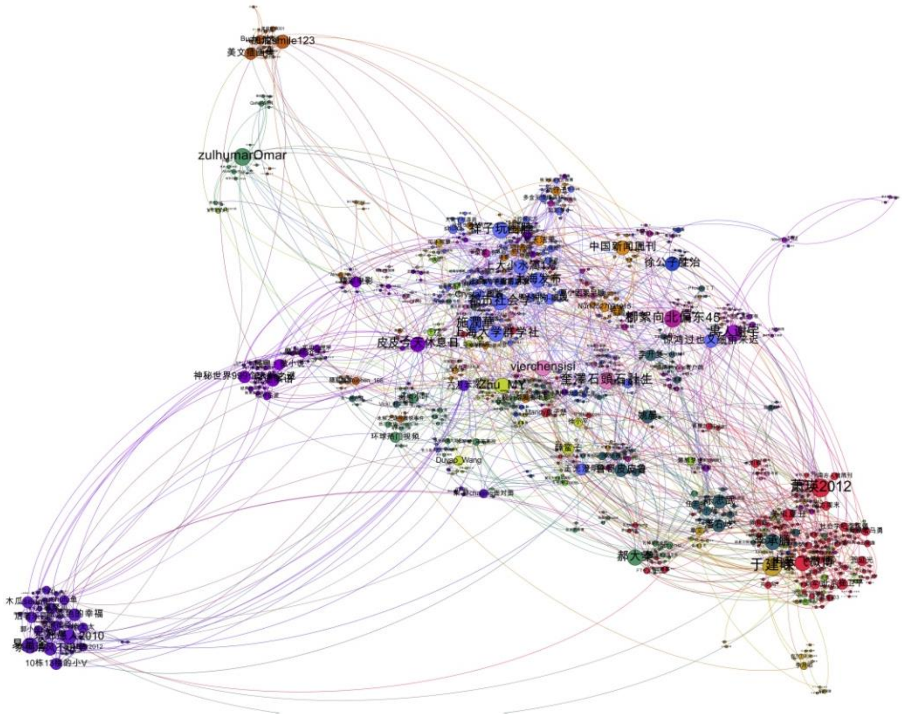

Figure 5. Real interactions between citizens

Conceptual model of citizen domain is developed from the interpretation of the results of computational model of citizen domain. Computational analysis permits a better understanding of the interactions between citizens, the nature of problems, the emergent patterns and structures of organization during interactions. The simulation of the flow of the citizens from main hospitals of Shanghai shows what are the accessible zones that the citizen reach travelling by subway or by foot during 30 minutes (Figure 4). The design for configuration of the city should consider the optimal distribution of the hospitals.

4.2 Discussion and comparison

Models of matrix of engineering modelling analysis are synthesized in Figure 2. Engineering design can seen be as a process of transformation of abstract models into concrete models from citizen domain to process behaviour domain. A city-design can be considered as complex object to be improved. The analysis of the design from the co evolution function/structure point of view is a central point for reflexive management of design activity (Choulier, 2011). In this context, different engineering design models for design of a complex city like Shanghai can be drawn from matrix of engineering modelling analysis. Figure 6 represents the well known FBS model proposed by Gero and Kannengiesser (Gero and Kannengiesser, 2002) and proposed alternative models. From this representation, the positions of Suh's and Yoshikawa's theories (Suh, 1990; Yoshikawa, 1981) can be questioned, too.

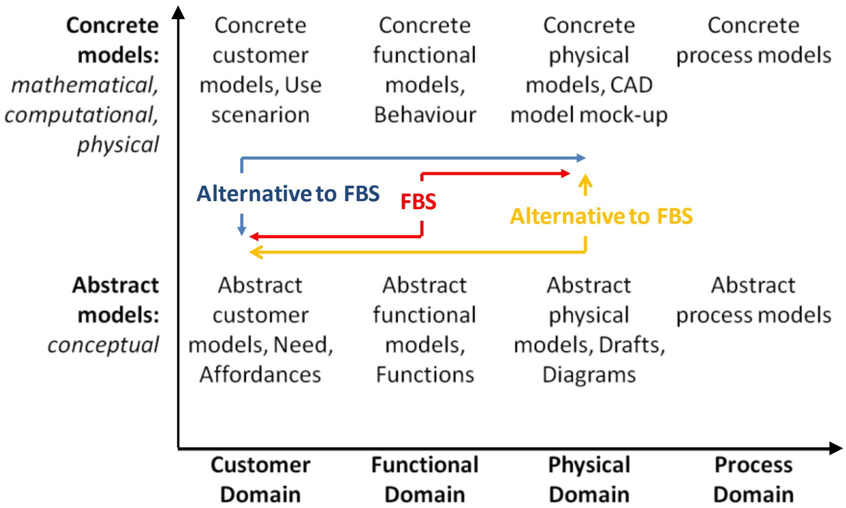

Figure 6. FBS and proposed alternatives

2 CONCLUSIONS

A model for describing the engineering modelling knowledge within an approach which encourages a systematic design of a complex city in practice is presented in this paper. A complete engineering modelling analysis is necessary for understanding and discovering the problems and for a good project management. The framework captures the knowledge of design engineers through the building models. The application shows that, considering the city as a living body, experimental model is a key for discovering the problems in the design of the city. The application has also demonstrated in practice, that iterative developing customer model, from concrete to abstract, permits to establish and to evaluate the conceptual model. The proposed framework can be used also for the diagnostic of the engineering design process. Finally, the proposed framework shows that engineering design theories and practices can successfully applied in the engineering design of complex city. Future work will include assessing the importance of the roles of citizens. How the citizens' differences can be considered and how these differences can be integrated into the proposed approach is another relevant issue. The fuzzy behaviour of citizens for consensus seeking in different problems and its dynamic modelling is a point to be considered (Ostrosi et al.). The task of modelling these problems and relating them to each other would be a challenging endeavour which requires more powerful theory.

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