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FORMALIZED REQUIREMENTS MANAGEMENT IN THE BRIEFING AND DESIGN PHASE, A PIVOTAL REVIEW OF LITERATURE

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SUMMARY: *The aim of this article is to provide a knowledge base for developing further theoretical frameworks and conceptual models that support IT-implementation for formalized requirements management in the briefing and design phases. Related standards or technology-supported methods are not within the immediate focus area of this article. During the briefing and design phase, a wide range of requirements are articulated, documented, communicated and iteratively evaluated and modified. Issues with addressing and implementing such requirements are more common to the architecture/engineering/construction/operation (AECO) industry compared with other industries. Earlier theoretical propositions mainly originating from cognitive science could shed new light on how information technology (IT) developments may be best exerted for formalized requirements management. For conducting this literature review, a framework suggested by vom Brocke et al. (2009) and a taxonomy developed by Cooper et al. (1998) were implemented. This review has its focus on the central issues of the reviewed articles. The analysis process follows an espousal position and the organization of the findings is conceptual. Through analysis and synthesis of literature, major characteristics and dynamics intrinsic to requirements management in the AECO industry have been identified. Moreover, a number of theoretical views on design and validation processes namely Pattern Language, Schema Theory (Chan, 1990) and the theory of axiomatic design (Suh, 2001) have been revisited with the aim of disclosing their take on formalized requirements formulation and modification. As a prerequisite for developing further theoretical grounds for formalized requirements management, terminological and taxonomic ambiguities throughout the requirements management discourse have been notified. Inconsistent interpretations of such terms as objective, goal, constraint, criteria, variable, parameter and attribute throughout literature have been extracted and presented in both verbal and diagrammatic formats.*

KEYWORDS: *Building requirement, Formalized requirements management, Design, Briefing, Constraint, BIM, object-based*

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1. INTRODUCTION

A client-centric approach to production and its associated routines for quality control has for long been a central concept in industrial fields (Akao, 2004, Lindahl and Ryd, 2007, Tzortzopoulos et al., 2006). Accurate documentation, analysis and communication of the clients' requirements on final products are essential to this approach. To realize this, issues such as undecided technical contents, never-ending changes of specifications and divergent interpretations by different actors should be overcome (Almefelt, 2005, Karlsson et al., 1998).

A parallel can be drawn to the AECO industry: while a shift from project-centric to product-centric processes in construction is inevitable (Karrbom Gustavsson et al., 2012, Koskela and Kagioglou, 2005), current routines for requirements management do not yet support such a shift. The AECO industry needs to become more industrialized and automated (Warszawski, 2003), which calls for more effective methodologies and systems for requirements management and progressive evaluation and validation of design alternatives.

During the briefing and design phase, a wide range of requirements are elicited, articulated, documented, communicated and iteratively evaluated. Issues with addressing and implementing such requirements have been more prevalent in the AECO industry compared with other industries (Ahmed et al., 2003, Jansson et al., 2010a). Consequently, the actual performance of the final products often largely diverge from the initial goals of projects (Kiviniemi, 2005). This could be attributed to the temporary nature of construction projects, one-of-a-kind products, lower and more dispersed levels of IT (Information Technology) literacy, conservatism and insufficient innovation in construction (Turk, 2006). For whatever reason the divergence from the initial goals of the construction project occurs, formulation and documentation of the specifications in formal and clear terms would facilitate further evaluation of requirements fulfilment.

Formalized requirements management in building design is not a new topic for scholars in the field of design methodology. Already in the mid-twentieth century, abrupt social, cultural and technological changes in societies and introduction of new building materials and systems called for a more transparent, democratic and scientific approach to design as opposed to the established though unjustified design traditions of the time (Lawson, 2006). In response and with the aim of maintaining a collective control over designers through inspection and evaluation of their design choices (Jones, 1992), a wealth of new design theories were devised mainly grounded on the notion of formalized requirements management. Such theoretical propositions often originating from cognitive science could shed new light on how IT developments may be best exerted for formalized requirements management.

The urge for formalized requirements management has been echoed also in contemporary research (Tse et al., 2005). There are many indications in the literature that new building information management technologies such as Building Information Modelling (BIM) could also be used for formalized requirements management i.e. as an integrated part of the iterative design and validation procedures (Arayici et al., 2005, Kiviniemi, 2005, Teicholz, 2013). Kiviniemi (2005) first introduced the concept of linking the formalized and machine-readable requirement models to building models. Other scholars have also emphasized the potentials of object-based requirements management and design validation for minimizing the deviation between the initial goals of construction projects and the final built entities and thereby promoting a more client-centric AECO industry (e.g. Arayici et al., 2005, Eastman et al., 2011, Eastman and Siabiris, 1995, Ekholm, 2011, Haymaker and Fischer, 2008, Jansson et al., 2013, 2010a, Parsanezhad and Tarandi, 2013, Tarandi, 2012). Even a number of commercial software applications such as dRofus, Solibri Model Checker and Onuma Systems have been developed for this purpose.

The theoretical grounds for formalized requirements management need, however, to be developed further. Based on the results of a survey distributed among AECO professionals in Hong Kong, Ugwu (2005) identified the urge for developing a robust knowledge management framework for documenting multidimensional user requirements during the early phases i.e. briefing and design. The AECO-specific theoretical grounds for IT-based information management such as BIM frameworks (Jung and Joo, 2011, Succar, 2009) have been articulated at such generic levels that could hardly be applied to such specific fields as requirements management. On the other hand, BIM-based applications are becoming more widespread across the AECO industry at an increasing pace and the failure to establish theoretical grounds that address the new trends in sufficient level of granularity could result in widening the gap between theory and practice.

The aim of this article is, thereby, to provide a knowledge base for developing further theoretical frameworks and conceptual models that support IT-implementation for formalized requirements management in the early phases i.e. briefing and design. To realize this, a diverse set of earlier theoretical takes on building requirements management and design methodology have been revisited and reviewed in search of theoretical grounds that could clarify:

- How building requirements could be documented in a formalized way and communicated in an automated fashion.
- How the initial building requirements could be updated during the iterative design process.
- How the documented building requirements could be continually acknowledged by designers and integrated into the design process and incremental validation of design alternatives.

As declared earlier in the aim statement, the temporal scope of this study is limited to the initial briefing and design phases where around 80% of the costs of construction projects are determined (Bruce and Cooper, 2000). The rationale is that a whole-life approach to construction has essential implications for formalized requirements management in the early phases i.e. briefing and design (Jansson et al., 2010a, Owen et al., 2010, Tarandi, 2011). Moreover, the theoretical focus of this article is the cognitive aspects of building requirements management. The organizational and social aspects of the phenomenon have just been touched upon here. So are related standards or technology-supported methods for formalized requirements management.

In section 2, the methodological framework governing how this literature review has been conducted is clarified. Section 3 embraces the major characteristics and dynamics that are intrinsic to requirements management in the AECO industry. Section 4 provides theoretical insights into the design and validation process and its relation to requirements formulation and modification. Sections 5 and 6 respectively address terminological and taxonomic ambiguities throughout the requirements management discourse which precede a short report on more recent advances in formalized requirements management presented in section 7. Section 8 provides a brief critical reflection on this study as a whole which is followed by a summary of the findings in section 9.

2. METHODOLOGY

A framework for reviewing literature developed by vom Brocke et al. (2009) was used in the conduct of this research. Using a framework for conducting this literature review was per se a response to the plea for more rigor in performing literature reviews by vom Brocke et al. (2009). Their proposed framework comprises five consecutive stages which could be iterated for improving the findings: 1) definition of review scope, 2) conceptualization of topic, 3) literature search, 4) literature analysis and synthesis, and 5) research agenda.

2.1 Definition of review scope

As recommended by vom Brocke et al. (2009) and demonstrated in Table 1, the scope of the review (stage 1) has been defined based on the taxonomy developed by Cooper et al. (1998): the focus of the review in this study (1-1 in Table 1) is the theories as well as the outcomes of the reviewed works; the goal of the study (1-2 in Table 1) is integrating the central concepts introduced or implemented in the reviewed works in search of the theoretical grounds beneficial for IT-based formalized requirements management; the findings have been organized and presented through different sections and subsections primarily with regard to the central concepts they convey. In section 7.2, different initiatives are presented in a historical order (1-3 in Table 1); this work is not a neutral representation of the contents, rather aims to highlight those theoretical propositions around formalized requirements management that could support use of new IT developments in construction for requirements management (1-4 in Table 1); the target audience of this study is scholars in the fields of construction IT and building information management (1-5 in Table 1); and finally, only those articles that embrace central and pivotal contents in the subject area of requirements management in the AECO industry have been covered here (1-6 in Table 1). Organization of the findings of literature reviews in a concept-centric fashion has been recommended by Webster and Watson (2002).

Through Table 1, primary choices for this study have been marked with grey backgrounds, bold texts and surrounding frames; while secondary choices have been marked merely with grey backgrounds.

TABLE 1: Definition of the review scope (stage 1 of the framework for literature review)

Characteristic	Categories			
1-1- Focus	Research outcomes	Research methods	**Theories**	Applications
1-2- Goal	Integration	Criticism	**Central issues**	
1-3- Organisation	Historical	**Conceptual**	Methodological	
1-4- Perspective	Neutral representation	**Espousal position**		
1-5- Audience	**Specialized scholars**	General scholars	Practitioners/politicians	General public
1-6- Coverage	Exhaustive	Exhaustive and selective	Representative	**Central/pivotal**

Scope : intended scope (primary) **Scope** : intended scope (secondary)

2.2 Conceptualization of topic

The main themes deployed for structuring the findings (stage 2 of the framework for literature review) are building requirements and the design formation and validation processes. These concepts were designated with regard to the aim of the article and delimited to the scope of this study as articulated in section1.

2.3 Literature search

As previously clarified through Cooper's taxonomy for definition of the scope of the review, it was not intended to provide an exhaustive coverage of the articles in the subject area of building requirements management here. The literature search process (stage 3 of the framework for literature review) was, therefore, not limited to such structured routines as keywords search. Instead, investigation of each of such distinguished theories as Schema Theory and Pattern Language was done through their corresponding literature as well as further complementary reading for each theory. Such resources date back to around half a century ago.

Moreover, a search for all types of materials published in the last 20 years was performed using a combination of the search terms 'requirements management' and 'construction' on the web-based database, Google Scholar. Top results were screened initially with regard to their titles. Where titles were relevant and sources were reliable, full-text versions were retrieved. Through a careful monitoring of the abstracts, articles that appeared to have some potential to support formalized requirements management were identified and reviewed thoroughly and relevant contents were extracted. When necessary, backward search was conducted through articles and books that had been cited by the reviewed articles.

2.4 Literature analysis and synthesis

Subsequently, extracted materials were summarized and re-organized using the main concepts as introduced in section 2.2. Analysis and synthesis of the material in each subject area was performed with regard to the choices of focus, goal, perspective, audience and coverage as stipulated in section 2.1.

2.5 Research agenda

The themes introduced in section 2.2 were used as the main headings for structuring and reporting the findings. With regard to the overall aim and scope of the research, further sections were added to address uncovered issues. As specified in section 2.1, the findings have been mainly organized and presented conceptually. The contents of section 7.1 are, however, presented in a chronological order.

3. REQUIREMENTS MANAGEMENT IN THE AECO INDUSTRY

Requirements on buildings may pertain to different lifecycle stages. Some requirements are applicable to the entire lifecycle of buildings e.g. sustainability, environmental consequences and energy consumption; some are specific to the construction phase e.g. constructability and logistics (Wikberg, 2011); some requirements address general qualities of the final product such as aesthetics and attractiveness; while some other requirements are more detailed functional criteria on the final product e.g. light intensity, air quality and acoustic (Eastman and Siabiris, 1995). Whichever temporal stage the requirements are attributed to, they should all be considered, defined and addressed early in the briefing and design phase in order to curb the costs later in the process.

According to the findings of a study by Ye et al. (2009), the top major concerns among practitioners in the AECO industry in order of importance are energy reduction (during operation of the building), sustainability (with a lifecycle approach), building lifecycle economy, building performance, end-user productivity, end-user comfort and wellness, flexibility (e.g. adaptability, multi-functionality), quality of construction (e.g. material durability), safety, social acceptability, construction methods (i.e. on-site or prefabrication), construction time, cost efficiency and capital cost of construction (Ye et al., 2009). They regard the above as the major categories of through-life requirements on buildings and suggest a methodology for subsequently capturing, analysing, verifying, consolidating and actualizing requirements as such. Their methodology does, however, not offer concrete guidelines for measuring and evaluating the above requirements at an operational level. The categories of requirements and the methodology suggested by Ye et al. (2009) are built upon the findings of survey questionnaires and interviews with actors from seven different groups of stakeholders i.e. infrastructure, regulatory bodies, support services, occupants, constructors, professional teams and clients.

According to Fiksel and Dunkle (1992), ‘requirements management’ could be defined as “the process of creating, maintaining, and testing requirements“ (Fiksel and Dunkle, 1992, p. 231). This definition is sourced from the integrated enterprise management domain. This compendious definition covers both the important areas of requirements formulation (as addressed in this section) and validation of design alternatives against requirements (to be addressed in section 4). Requirements management in the AECO industry is sometimes regarded as a subset of the broader domain of industrial manufacturing requirements management (Arayici et al., 2006). However, the significance and nature of the role of the client in the AECO industry is largely different from that of the corresponding role in other industries. In more automated industries, the roles of the non-technical customers and the semi-expert clients are often separated giving space to more technical and sophisticated requirements management routines. In the AECO industry, however, the distinction between the client and customer roles is often blurred (Lawson, 2006) which calls for different approaches to requirements management compared with other industries.

Even though the most fundamental requirements are formulated by the client, the eventual set of requirements is collaboratively developed by a broad spectrum of stakeholders. The client, per se, could be a user client (often in the case of smaller projects) or a paying client (common to larger building or infrastructure projects). The latter serves as the middleman between end-users and AECO actors (Lawson, 2006). The end-user group itself could comprise inhabitants, building administration staff, operations and maintenance personnel and external service providers. Such an extensively heterogeneous group of stakeholders would impose diversified and sometimes conflicting requirements on both the product and the process of construction (Christiansson et al., 2009). The AECO actors such as the architect, engineers and construction manager will, in turn, contribute to refining the initial requirements and also suggesting further requirements themselves. The scope and magnitude of the contribution of each of the above actors to formulation and elaboration of requirements is largely different from one project to another and often rests on such project-specific factors as procurement method, financing structure, and the stakeholders’ attitudes, expertise and organizational traits (Winch, 2012, Yu et al., 2010). Such a broad diversity of actors involved in requirements formulation and their varying levels of involvement in the requirements definition process is a major challenge to formalized requirements management.

Moreover, the process of defining and refining requirements is incremental and iterative (Fu et al., 2007). Goals and obstacles to achieving goals are not always clearly acknowledged in the beginning (Lawson, 2006). Clients often have a vague perception of their needs and preferences (Kamara et al., 2002, Zeiler and Savanovic, 2007). Architects try to concretize and document such obscure ideas via design protocols as verbal and visual descriptions. Design protocols often include valuable but unstructured information that could not always be expressed in formal terms (Akin and Lin, 1995, Gero and Mc Neill, 1998, Jansson et al., 2010a).

Any theoretical framework for conceptualizing and supporting formalized requirements management in the AECO industry should appropriately address the challenges mentioned above. Moreover, it is through the iterative processes of formation, evaluation and validation of design alternatives that requirements are comprehended, implemented, developed further and consolidated. It is therefore crucial to theoretical frameworks for requirements management to also embrace the procedural aspects of the design and validation processes. Fiksel and Dunkle (1992) emphasize the interrelationship between requirements definition and validation by defining ‘requirement’ as “a description of a set of testable conditions applicable to products or processes” elaborating that “a requirement is said to be satisfied by a product (or process) if a test reveals that the described conditions are met by that product (or process)” (Fiksel and Dunkle, 1992, p. 231). Cavieres et al. (2011) also address the fact that requirements development is closely intertwined with evaluation of design alternatives. The demand for testability of the requirements is, in fact, one of the major motives for implementing formalized requirements management in the AECO industry (Kiviniemi, 2005). This will be addressed in more details in section 7.

4. THE DESIGN FORMATION AND VALIDATION PROCESS

Stated briefly, design is an interaction between what is needed i.e. requirements and how that need is satisfied i.e. the designed solution (Kals and van Houten, 2013). Arguing that the design work is a mix of systematic and chaotic ways of thinking, designers have for centuries preferred to prioritize the outcomes of their intellectual enterprise over its formation process and regarded their work as untraceable processes and unaccustomed workflows (Lawson, 2006). Despite all the fuzziness about the design process, the basic characteristics of conventional building design practices have been extensively studied (e.g. by Chan, 1990, Darke, 1979, Galle and Kovács, 1992a, Schoen, 1988) and many efforts have been made to develop models and theories that conceptualize the building design discipline (e.g. by Akin, 1978; Akin and Lin, 1995; Gero and Mc Neill, 1998).

Lawson (2006) portrays design as the process of seeking an integrated solution for a given problem. The design problem, according to him, is hierarchical, multidimensional and interactive. The solution is often sought through a perpetual span comprising drawing and redrawing. The iterative attribute of design has also been accentuated by other scholars. Eastman and Siabiris (1995), for instance, describe the design process as an iterative sequence of problem formulation, synthesis and analysis. Lera (1983) asserts that the outcomes of each round of developing and evaluating solutions informs the successive round. Eberhard (1970) clarifies how escalation and regression of design problem further provokes the iterative cycles of the design process. Escalation implies reconsidering the initial problem at a broader scope and taking other elements from the surrounding environment into the design problem at hand; whereas regression implies downsizing the problem to a smaller part of it (Eberhard, 1970). Escalation and regression of the design problem are necessitated when new information or insights are revealed to the designer.

The Marcus/Maver representation of building design as summarized by Lawson (2006) demonstrates a simultaneously iterative and progressive process. According to this model, the consecutive steps of analysis, synthesis, appraisal and decision-making are iterated as the level of detail of the proposed solution escalates from outline proposals through scheme design to detail design: through the analysis phase, the design problem is refined and reorganized; one or more solutions are generated through the synthesis phase; suggestions are critically evaluated during the appraisal phase; and then the suggested solution is finalized (Fig. 1). Even though the Marcus/Maver model explains some fundamental features of the design process, it is based on two underlying assumptions that do not always hold in real-world design practices: that the iterative loops occur exactly as presented in the model; and that the level of detail of the proposed solution constantly increases over time (Lawson, 2006). Lindahl and Ryd (2007) notify that during the iterative process of developing the final design solution, many trade-offs among goals and objectives could be made which are motivated by the results of evaluation of design alternatives as well as the unending interplay of the involved actors and their changing priorities and preferences.

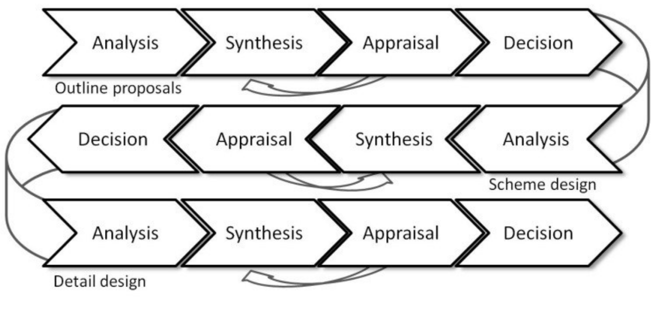

FIG. 1: Marcus/Maver representation of the building design process drawn after Lawson (2006)

Models for building design and validation of design alternatives as conceptualized in this section were apparently simplified abstractions of real-world processes. A more in-depth understanding of such processes requires more profound and inclusive theoretical frameworks.

4.1 Some theoretical stances on building design

4.1.1 A systems approach to design

Ekholm (2011) emphasizes that the building design process should be understood as a sociotechnical system. The three major areas of system development according to Ross and Schoman (1977) are:

- Context analysis: why the system should be designed and what its boundary conditions are;
- Functional specifications: what the system and its functions are; and
- Design constraints: how the system is constructed and implemented.

Building requirements could be associated with any of the above fields. According to this model, the point of departure for requirements definition would be the contextual concerns followed by a more detailed description of the functional specifications of the envisioned building and eventually formulating the more concrete constraints pertaining to construction and implementation. In the case of functional specifications of buildings, Markus (1967) suggests a four-function model. In his model, building as a system could be conceptualized in four different ways: as a system of physical components, an environmental system, an activity or behaviour system and an organizational system. A systems approach to building proclaims that a building is not a mere industrial product; rather is conceived, realized and deployed by human actors in an organizational context. Other theoretical approaches to building design process are often more illuminative about formation and transformation of information at a micro level, but could be inattentive to the social and organizational attributes of building design.

4.1.2 A cognitive approach to design

A considerable share of theories on building design has its roots in cognitive science (e.g. theories developed by Goldschmidt, 1991, Schön and Wiggins, 1992, Stenning and Oberlander, 1995, Suwa et al., 1998). The rationale is that design alternatives are to a great extent shaped through humans' intellectual feats (Gero and Mc Neill, 1998). In a like manner, Lawson (2006) asserts that design "involves a sophisticated mental process capable of manipulating many kinds of information, blending them into a coherent set of ideas and finally generating some realisation of those ideas" (Lawson, 2006, p. 14). Cognitive theories on design methodology try to unravel the building design process and develop concepts and constructs that help comprehending, analysing and eventually cultivating building design as an influential sequence in the AECO industry.

4.1.3 Schema Theory

Heuristic design methods (Lawson, 2006) involving unverifiable routines result in accumulation of design knowledge in tacit forms. Conceptualizing conjectural units of information is a common theoretical approach for promoting the shift from heuristic design methods to more rational and formal ways of designing buildings. A prominent example of theoretical approaches as such is the 'Schema Theory' which was developed by Rumelhart and Ortony (1976) based on the principles of the 'Semantic Network Theory' introduced a decade earlier by Collins and Quillian (1969). Schema Theory suggests conceiving small inter-linked bundles of information called 'schemata' which are appropriate to humans' cognitive abilities. The concept of schema has also been used by experimental psychologists such as Bartlett and Bartlett (1995) as a means for presenting an internalized mental image of the external world: an articulated organization of past experiences with the aim of orchestrating future events.

Chan (1990) suggested using schemata as an information management structure for buildings. According to him, design solutions are produced by activating design constraints and their associated rules in memory. Thereby, he introduced a set of guidelines termed as 'perceptual tests' for evaluating design alternatives against project goals. Chan (1990) was in fact the very first theoretician who used the Schema Theory for developing an integrated model for building requirements management, building design and validation of design alternatives (see Fig. 2). According to him, design constraints could be considered as the most important schemata in the design phase. Carrara et al. (1994) extended the Schema Theory to explain how to simultaneously capture descriptive and operational building design information through schemata. Objectification of building elements, their properties and – more recently – building requirements in semantic building models through BIM environments follows the same principles for building information management as conceptualized through the Schema Theory: devising small perceptible units of information called ‘objects’ for representing the real world. The notion of ‘object’ in this sense will be elaborated in more details in section 5.

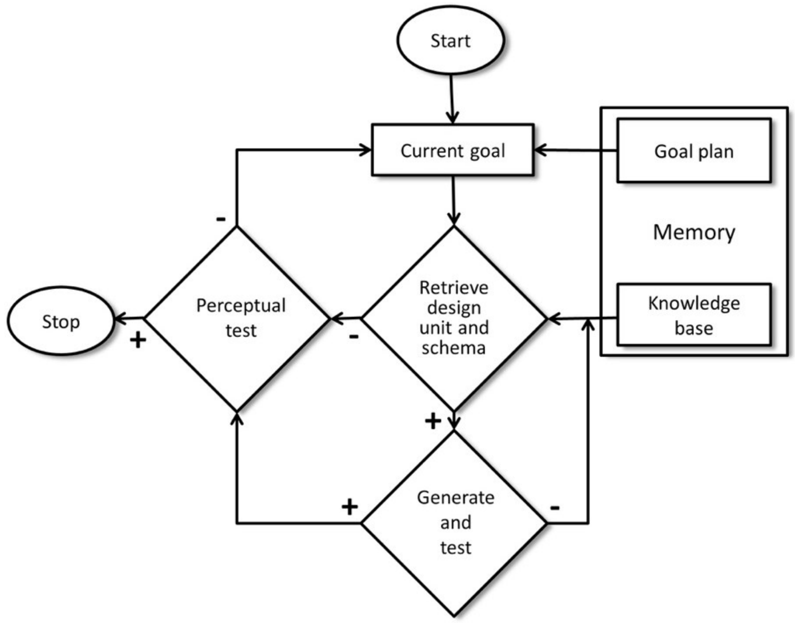

Fig. 2: The integrated model for building requirements management, building design and validation of design alternatives based on the Schema Theory; drawn after Chan (1990)

4.1.4 Pattern Language

Another influential theory in the field of building design is Christopher Alexander’s ‘Pattern Language’. By and large, the Pattern Language theory promotes use of rational and explicit rules for building design (Galle and Kovács, 1992a). The theory suggests a set of structures for compiling architectural design knowledge in a modular and yet customizable and reusable form (Alexander et al., 1977). The Pattern Language theory regards building design alternatives as responses to specific structures or ‘patterns’ of given problems (Chermayeff and Alexander, 1963). Lawson (2006) refers to Alexander’s suggestion for developing graphical representations of the structures of non-visual problems as a rational alternative for architects’ drawing boards. Rational approaches as such were intended as a means for demystifying the design process, facilitating evaluation and validation of design alternatives and thereby maintaining collective control over designers’ activities (Jones, 1992).

Pattern Language inspired a vast number of other theoreticians in the field of design methodology and was subjected to both appraisal and criticism (Dovey, 1990, Galle and Kovács, 1992b, Schoen, 1988): Galle & Kovács (1992a), for instance, envisioned design systems that were capable of automatically identifying whether an evolving design solution satisfied some specific ‘pattern’ or not. Broadbent (1973), however, described Pattern Language as a mechanistic view of design. Some potential drawbacks of Pattern Language according to Lawson (2006) are:

- Some requirements are not decisive in forming the final solution.
- Due to correlated or missing values, no distinctive or exhaustive list of requirements could be set in the beginning.
- There are not always clear and explicit methods or metrics available for evaluation and validation of requirements.

Yet, the Pattern Language theory established a new paradigm in building design and could be considered as a significant step towards formalized requirements management. However, such deficiencies and inadequacies as mentioned above compelled development of further theoretical frameworks.

4.1.5 The theory of axiomatic design

The theory of axiomatic design is a systems design methodology developed by Suh (2001). It is mainly grounded on two axioms: the independence axiom prescribing independent functional requirements and the information axiom ruling that the information content of design should be minimized. The independence axiom is realized through a diagonal or triangular matrix of requirements. The ambition is to minimize the number of off-diagonal elements in design matrices of design alternatives (Jansson et al., 2013). There is one other central concept in the theory of axiomatic design: the concept of zigzagging implies moving back and forth between functional requirements and design parameters through the hierarchical decomposition of the two categories. According to this view, the level of detail of design solutions increases incrementally as functional requirements are iteratively transformed to design parameters and implemented into the final integrated solution over the entire course of the briefing and design phases (Suh, 2001). Jansson et al. (2013) expanded the vision offered by the theory of axiomatic design so as to also cover the earlier and later stages of the supply chain of buildings. They introduce four consecutive domains of ‘customer’, ‘functional’, ‘physical’ and ‘process’ together with their associated requirement types respectively ‘customer attributes’, ‘functional requirements’, ‘design parameters’ and ‘production variables’. Bidirectional transformation of design information across these domains, according to the authors, is enabled through architectural, engineering and production views as well as formal constraints (Jansson et al., 2013). As a means for minimizing unnecessary iterations through the design process, the concept of concurrent engineering (Prasad, 1996) has been deployed as the basis for developing a broad range of recent design methodologies. A prominent example is Virtual Design and Construction (VDC) as conceptualized by Kunz and Fischer (2005) which deals mainly with the construction phase.

There is an abundance of theories that underpin a formalized requirements management practice. However, a fundamental challenge is that the terminologies and taxonomic structures that are used in the literature on requirements management in the AECO industry are not consistent.

5. TERMINOLOGICAL VARIATIONS IN THE FIELD OF REQUIREMENTS MANAGEMENT

Terms common to the literature on requirements management namely ‘objective’, ‘goal’, ‘constraint’, ‘criteria’, ‘variable’, ‘parameter’ and ‘attribute’ connote requirements at different levels of abstraction and maturity. These terms have though not always been used consistently which could deter a holistic conceptualization of the domain of requirements management in the AECO industry. Below, you will find a summary of taxonomic variations in the field of requirements management through literature:

The term ‘objective’ is quite often used for requirements on building at the highest granularity and the most abstract level. Carrara et al. (1994, p. 163) define ‘objectives’ as “desirable performances of a sought solution”. The definition of ‘objective’ as such directly addresses the performance rather than the specifications of the final product i.e. the building. Whereas terms such as ‘goal’ and ‘constraint’ are often used to explain the more detailed requirements on the final product in more concrete terms. Kalay (2004) defines ‘goals’ as subsets of interconnected constraints that designate specific performances in a formalized way. This view clarifies how each of the concrete and tangible descriptions of performances that constitute an overall design solution are realized through a corresponding set of constraints. Each set of constraints as such is aggregated into a distinct goal upon the briefing phase (Fig. 3).

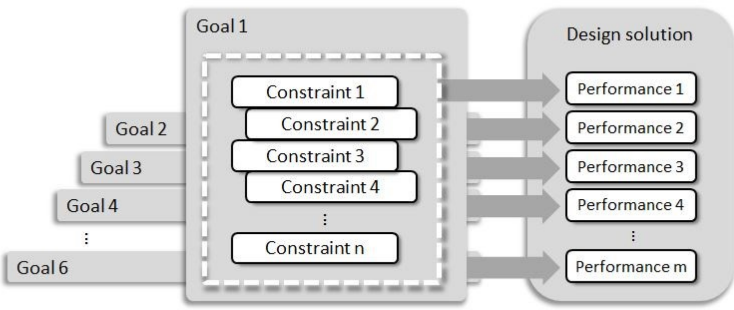

FIG. 3: Definition of 'goal' based on the notions of 'constraint' and 'performance' according to Kalay (2004)

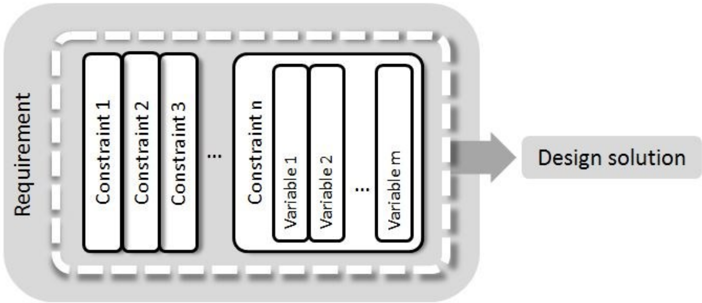

FIG. 4: Definition of 'requirement' based on the notions of 'constraint' and 'variable' according to Lottaz et al. (2000)

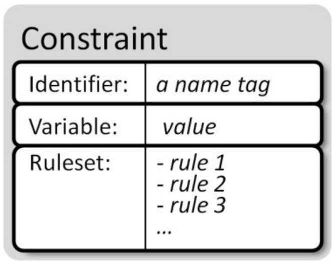

FIG. 5: A formal definition of 'constraints' based on the notions of 'identifier', 'variable' and 'rule' according to Chan (1990) and different types of rules according to Fiksel and Dunkle (1992

The term 'constraints', in turn, is defined as the "predicates that evaluate to true or false"(Eastman and Siabiris, 1995, p. 290). Constraints are used as restrictions that eliminate unacceptable solutions or as "bounds on acceptable solutions" (Kals and van Houten, 2013, p. 2). In this sense, constraints are different from other concepts that define requirements mostly in affirmative ways. Lottaz et al. (2000) suggest defining each requirement directly through its constituent constraints (Fig. 4). According to their proposed model, constraints are defined as "mathematical equations on continuous variables for specifying requirements" (Lottaz et al., 2000, p. 2). At a more detailed granularity, Lottaz et al. (2000) introduce 'variables' as mathematical constructs that enable defining each constraint in a formal way.

A common view is that requirements can be demonstrated as a set of constraints to be satisfied by proposed design alternatives (Chan, 1990, Eastman, 1994, Galle and Kovács, 1992b, Varejão et al., 2000). Chan (1990) designates different components of a design constraint schema as an 'identifier' (the name tag for the constraint), a 'variable' (which is attributed to the schema), a set of 'rules' (on how the constraint should be satisfied), and a 'value' for the variable (which is bound to a specific design unit) (see Fig. 5). According to Fiksel and Dunkle (1992), the rules within a constraint are the conditions that should be met by the final product through the requirements validation process and could be of textual (descriptions as text), pictorial (described with forms and diagrams), numerical (described as an acceptable range/set of values for specific variables) and logical types (described as an acceptable range/set of values for specific variables).

Constraints as such and their constituent rules are defined at building entities' level. For the sake of comprehensibility for human users, building entities are represented by 'objects' in contemporary building information management systems. The notion of 'object', which is now fairly established through BIM applications and databases, is in fact a present-day equivalent to the earlier concept of 'schema' as conceptualized by the Schema Theory (Rumelhart and Ortony, 1976). Based on the ontological clarifications provided by Bunge (1977), Ekholm (2003) defines the concept of 'object' as concrete or abstract entities for representing ideas, feelings or activities. Objects need to be defined together with their associated properties and are linked to other objects throughout their encompassing system via a number of relations. It is also possible to conceptualize constraints themselves as objects of the requirement type. Such an approach was implemented by

Jansson et al. (2010b) within a lifecycle-support building information management system using the Product Life Cycle Support (PLCS) standard (ISO, 2005).

Such terms as ‘variable’, ‘parameter’ and ‘attribute’ are deployed at a more detailed level of granularity. A prominent example is the terminology used by Jansson et al. (2013) in their elaborated model of requirements formation and evolution based on the theory of axiomatic design developed by Suh (2001). Through their procedural view, customer needs are determined as ‘attributes’; ‘requirements’ denote functional traits; ‘parameters’ are used for describing the designed solution; and ‘variables’ are associated with production of the finalized design solution. ‘Constraints’, on the other side, are considered as conditions that facilitate formalizing and transforming production variables through design parameters and functional requirements, backwards to customer attributes (see Fig. 6).

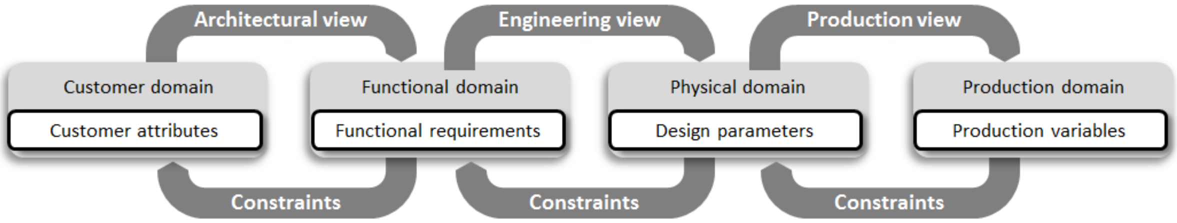

FIG. 6: The procedural model of building requirements according to Jansson et al. (2013) based on the theory of axiomatic design by Suh (2001)

The term ‘criterion’ is sometimes used as a synonym for requirement. According to Portillo and Dohr (1994), constraints are more restrictive and explicit; whereas criteria are more flexible and evaluative. In this view, requirements are used for defining the design solution at earlier stages; whereas criteria are applied a bit later for examining those solutions.

Table 2 demonstrates a brief glossary of the major terms in the domain of formal requirements management. The table embraces all terminological variations disclosed in this section. Each term – which is assumed to be the identifier for a certain concept – is coloured in a distinct way for highlighting how differently it has been used by different scholars.

6. TAXONOMIC VARIATIONS IN THE FIELD OF REQUIREMENTS MANAGEMENT

The epistemological ambiguities in the requirements management domain are not limited to inconsistent terminologies. Categorization breakdowns of the central concepts in the field by different scholars are also broadly divergent. A common criterion for classifying building requirements is how strict or flexible they are. Varejão et al. (2000) also Lawson (2006) designate two major types of requirements as hard (mandatory) and soft requirements. According to Varejão et al. (2000), examples of hard requirements are legislations, codes and standards; while soft requirements are project-specific ones that could be reformulated or mitigated. Hard requirements are often fairly detailed and focused on some specific aspect of design; whereas soft requirements could be of a more general nature (Lawson, 2006).

Concepts connoting requirements at lower granularity levels i.e. constraints and criteria are per se classified into different categories. A common measure for categorising constraints is whether they are originated from within the design problem or imposed by the surrounding environment. The former are, according to Lawson (2006) and also Kalay (2004), called internal constraints; while the latter are termed as external constraints. Internal constraints address the interrelations among building parts and elements such as room adjacency relationships. They constitute the main part of brief documents and are often presented as bubbles or flowcharts. External constraints, on the other hand, are used when one side of the relationship is outside the object to be designed e.g. constraints on production processes and site conditions. Internal constraints are generally more flexible than external constraints (Lawson, 2006). Kalay (2004) mentions gravity, wind resistance and building codes as examples of external constraints, and budget and number of rooms as examples of internal constraints. Candy and Edmonds (1997) refer to internal and external constraints respectively as performance and contextual constraints.

TABLE 2: Terminological variations in the domain of formal requirements management

Term	Relation (definition)	Term	Relation (definition)	Term	Source
Attribute	is defined as	Needs	of customers.		Jansson et al. (2013)
Constraint	is defined as a	Predicate	that take the values of true or false.		Eastman and Siabiris (1995)
	is defined as bounds and restrictions on	Design solutions			Kals and van Houten (2013)
	is defined as mathematical equations on	Variables	for specifying	Requirements	Lottaz et al. (2000)
	is made up of	Variables	and	Rules	Chan (1990)
	is defined as a	Condition	for transition from production	Variables	Jansson et al. (2013)
			through design	Parameters	
			through functional	Requirements	
			to customer	Attributes	
Goal	is made up of	Constraints	that specify	Performance	Kalay (2004)
Object	is defined as	concrete or abstract entities	for representing	ideas, feelings or activities.	Ekholm (2003)
Objective	is defined as a desirable	Performance	of a	Design solution	Carrara et al. (1994)
Parameters	describe	Design solutions			Jansson et al. (2013)
Requirement	is made up of	Constraints			Lottaz et al. (2000)
	is made up of	Constraints	to be satisfied by	Design solutions	Chan (1990), Eastman (1994), Galle and Kovács (1992b), Varejão et al. (2000)
	is defined as a	Functional trait			Jansson et al. (2013)
Rule	is defined as a	Condition	to be satisfied by	Design solutions	Fiksel and Dunkle (1992)
Variable	is used for supporting production.				Jansson et al. (2013)

Constraints could also be categorized based on their more intrinsic features: Lawson (2006) suggests a model of design constraints comprising the following types:

- formal constraints e.g. proportion, color and texture;
- symbolic constraints i.e. those conveying a message;
- radical constraints i.e. the very fundamental and influential constraints; and
- practical constraints e.g. those imposed by manufacturing, construction methods, maintenance and durability.

Varejão et al. (2000) suggest a more simple taxonomy for constraints comprising functional, formal and objective-based categories. They, however, use the more general term of ‘requirement’ instead of ‘constraint’. Another term that is occasionally used by scholars for suggesting alternative classifications of requirements is ‘criteria’. Portillo and Dohr (1994) enumerate five major categories of criteria used by designers as follows:

- symbolic criteria which address divine intentions of designers;
- compositional criteria which are related to forms and shapes;
- behavioral criteria originating from the users’ behaviors;
- preferential criteria reflecting the users’ preferences; and
- pragmatic criteria e.g. rules and costs.

For conceptualizing the object properties upon which constraints and criteria are defined and applied, Ekholm (2003) suggests a number alternative classification models: properties could be primary (those which are determined in objective ways indifferent of the observers) or secondary (those which are experienced and interpreted through the observers' senses); properties could also be classified as intrinsic (defined exclusively in relation to the host object) or reciprocal (defined based on the host object's relations with other objects). Through a different approach, properties could be considered as physical or cultural; where physical properties could be of functional, comparative and compositional types and cultural properties are divided in experimental, symbolic and administrative subcategories (Ekholm, 2003). Table 3 demonstrates a summary of the taxonomic variations for different concepts across the domain of formal requirements management.

TABLE 3: Taxonomic variations in the domain of formal requirements management

Term (concept)	Types	Source
Constraint	internal and external	Lawson (2006); Kalay (2004)
	performance and contextual	Candy and Edmonds (1997)
	formal, symbolic, radical and practical	Lawson (2006)
	functional, formal and objective-based	Varejão et al. (2000)
Criteria	symbolic, compositional, behavioural, preferential, pragmatic	Portillo and Dohr (1994)
Properties	primary and secondary	Ekholm (2003)
	intrinsic and reciprocal	
	physical and cultural	
Requirement	criteria and constraints	Portillo and Dohr (1994)
	hard (mandatory) and soft	Varejão et al. (2000); Lawson (2006)
Rule	textual, pictorial, numerical and logical	Fiksel and Dunkle (1992)

7. TOWARDS A FORMALIZED DEFINITION OF REQUIREMENTS

7.1 Building requirements management through mathematical expressions and formal methods

Despite all terminological and taxonomic ambiguities in the requirements management domain, the potential benefits of formal definition of requirements have been acknowledged by many scholars (see section 1). Arayici et al. (2006) suggest a fundamental shift from sequential thinking to structural thinking for facilitating formalization of requirements through the AECO industry. Lottaz et al. (2000) recommend using mathematical expressions for specifying constraints as a means for making information explicit and eventually avoiding conflict among stakeholders (Lottaz et al., 2000). Below, some examples of earlier attempts for defining building requirements as mathematical expressions are presented:

Varejão et al. (2000) define building requirements (R) as a set of individual requirements (r) which possess requirement qualifications (q) and requirement relationships (l):

$R = \{ < r1, q1, l1 >, < r2, q2, l2 >, \ldots, < rn, qn, ln > \}$ (Varejão et al., 2000) [1]

Requirement qualifications within this equation can be of the three types of requirement source (sc; the actor who sets the requirements), requirement importance (im; hard or soft requirements), and requirement type (t; functional, formal or objective-based):

$q ::= < sc, im, t >$ (Varejão et al., 2000) [2]

Despite its clarity and focus in expressing the concept of building requirement and its attributes in formal terms, the formula presented by Varejão et al. (2000) does not recognize the dynamic nature of requirements formation and evolution and the fact that requirements are incrementally defined through an interplay among the envisioned product and the designed solution. Through his theory of axiomatic design, Suh (2001) illustrates this dynamic aspect of requirements definition using the concept of design matrices. The coupling between functional requirements (FR) and design parameters (DP) is defined mathematically as:

$\{FR\} = [A]\{DP\};$ [3]

where A is the design matrix (Jansson et al., 2013) (see section 4.1.5).

Defining building requirements in such explicit forms as mathematical terms paves the way for developing comprehensive methods for formalized requirements management. Some examples of such methods according to Kamara et al. (2002) are Quality Function Deployment (QFD), Client Requirements Processing Modelling (CRPM), Total Quality Management (TQM) and Failure Mode and Effects Analysis (FMEA). CRPM consists of identifying client's requirements, sorting out requirements with regard to the priorities of the project, identifying design attributes and technical features of each requirement, specifying target or desired values, developing correlation matrices and determining absolute and relative weights of building requirements. The output for a requirements management procedure based on the CRPM method will be an ordered list of requirements where their corresponding attributes, units of measurement and desired values have been mentioned. CRPM has been presented using the IDEF-0 (Integration Definition Level 0) notation (Kamara et al., 2002). A major problem with such methods as CRPM is that implementing them could be time-consuming (Kamara et al., 2002). Integrating such methods into IT applications and object-based building models could be a viable fix to this problem.

7.2 Towards IT-based formalized requirements management

Augenbroe (1992) asserted that conventional design processes are inverse, interrogative and incremental. He contended that the IT-based building performance evaluation technologies of the time did not fulfil the demands of the design processes as such. Carrara et al (1994) suggested developing computational models that had the capacity to capture great numbers of prototypical design objectives and solutions to integrate the three main stages of a conventional design process i.e. definition of objectives, developing alternative design solutions, and evaluating alternatives against objectives. Gero and Mc Neill (1998) introduced a coding scheme for capturing information scattered around design protocols and channelling that information to validation procedures. In their proposed scheme, the design process is composed of three episodes: proposing solution, analysing solution and explicit strategies. Lottaz et al. (2000) developed a web-based application called SpaceSolver for expressing design constraints and their interdependencies in a formal way. Their model was implemented through two construction projects. Tarandi (2002) suggested a new type of space object that supported the iterative process of definition of requirements through versioning. Examples of requirements to be attached to space objects in his proposed initiative were spatial proximity and minimum required area for different rooms and spaces. As part of the CIFE's (Center for Integrated Facility Engineering) VDC framework, Kiviniemi (2005) proposed a requirements model specification consisting of 300 requirements in 14 main categories and 35 subcategories. The model was based on Industry Foundation Classes (IFC) specifications and aimed to link formally expressed requirements to object-based design-intent models.

Another parallel effort for formalizing requirements documentation and validation using object-based models is the nD-modelling initiative developed at the University of Salford: Tse et al. (2005) conducted a pilot research aiming to integrate time, cost, buildability, accessibility, sustainability, maintainability, acoustics, lighting and thermal requirements with an object-based 3D model. Fu et al. (2007) developed a space centered computer-aided design (CAD) tool for requirements management in briefing and conceptual design phases for healthcare buildings. The tool was embedded in Autodesk AutoCAD. The focus was using visual tools for documenting and communicating design guidance. Assuming costs of the project as the central criteria, Lee et al. (2008) developed an information model and its associated digital application for cost-based decision making for the interior design of large-scale apartments. Tarandi (2011) conceptualized a model server based on IFC (ISO, 2013) and PLCS (ISO, 2005) standards called BIM Collaboration Hub for supporting continual documentation, updating and communication of building information through the entire lifecycle of buildings. The principles of this model had been previously implemented for classification and transformation of performance requirements (Jansson et al., 2010a). Christiansson et al. (2011) presented a method for actively involving end-users in expressing their expected requirements on the building and then consolidating and integrating those needs in the form of a design alternative with the aid of a collaborative virtual reality environment. Jansson et al. (2013) proposed an IT-based framework for requirements management of energy performance of design alternatives. Their framework was based on the theory of axiomatic design (Suh, 2001) as previously clarified in section 4.1.5.

8. FURTHER REMARKS

A formalized approach to requirements management could also have its downsides: activities that would occur in the designed building could be difficult to define accurately (Eastman and Siabiris, 1995) which impedes accurate definition of the requirements imposed by those activities. Moreover, high degrees of formalization may hamper flexibility (Christiansson et al., 2009). The level of maturity of building requirements should therefore be designated with regard to the specific attributes of each project such as social and organizational factors. As an example of the organizational aspects, the level of maturity of requirements could be closely linked to the level of maturity of the client's business operations (Barrett and Stanley, 1999, Tzortzopoulos et al., 2006). Social aspects are not of lesser importance: consecutive communication, comprehension and realization of the requirements occur through constant interaction and collaboration among different actors. Success of such interactions could, in turn, be a subjective matter (Siva and London, 2012). Conflict and tension over more control is a constant element of planning and design activities (Lawson, 2006). Such social and organizational dynamics as authority distribution, conflict negotiation and trade-offs between design criteria and truth maintenance (Augenbroe, 1992) will inevitably influence the process of formulation, documentation, communication, validation and reformulation of building requirements. As specified earlier in section 1, however, the organizational and social aspects of building requirements management were not the focus of this article and were just briefly touched upon in section 4.1.1.

9. CONCLUSION

For avoiding wasteful expenditures later in the process, requirements pertaining to different lifecycle stages should be fully or partially addressed already in the briefing and design phase. A multitude of actors often with conflicting needs and objectives are engaged in requirements definition. The final definitions of requirements are often scattered around a wide variety of documents and resources in different formats. Capturing requirements is an iterative and incremental process which is closely intertwined with the design formation and validation process – which is itself an iterative and fuzzy process.

There is an abundance of earlier theories in design methodologies that could be beneficial for conceptualizing IT-based formalized requirements management. A systems approach to design provides the capacity for covering all different aspects of the design process, but may not be as useful when implementing in more detailed contexts. For the latter purpose, such cognitive theories as Schema Theory (Chan, 1990) and Pattern Language (Alexander et al., 1977) provide more relevant insights in the context of formalized requirements management. The theory of axiomatic design (Suh, 2001), however, better covers the procedural aspect of defining and refining building requirements. At the implementation level, concrete methodologies such as concurrent engineering (Haymaker and Fischer, 2008, Prasad, 1996) have been developed more recently to improve requirements formulation and implementation in real-world construction projects.

The discourse of formalized requirements management relies on a broad range of notions such as 'objective', 'goal', 'constraint', 'criteria', 'variable', 'parameter' and 'attribute' which are used in different ways by different scholars. The types of requirements, criteria, constraints and object properties as enumerated by different scholars also vary significantly. A prerequisite for developing theoretical frameworks that underpin leveraging IT for formalized requirements management is stipulating standardized terminology and taxonomies for this domain.

In recent decades, a significant number of initiatives for IT-based formalized requirements management have been introduced. Almost all such initiatives have their roots in mathematical expressions of building requirements. Nevertheless, not all efforts as such are grounded on established theoretical frameworks or, if so, unequivocally clarify how they correspond to their underlying theoretical grounds. This article could help strengthening the theoretical rigor of future conceptual models and implementation initiatives for IT-based formalized requirements management through presenting a number of potentially beneficial theories and their associated concepts in a comprehensive and concise fashion.

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11. APPENDIX A: ABBREVIATIONS

AECO	architecture/engineering/construction/operation
BIM	Building Information Modelling
CAD	computer-aided design
CRPM	Client Requirements Processing Modelling
FMEA	Failure Mode and Effects Analysis
IDEF-0	Integration Definition Level 0
IFC	Industry Foundation Classes
IT	information technology
PLCS	Product Life Cycle Support
QFD	Quality Function Deployment
TQM	Total Quality Management
VDC	Virtual Design and Construction