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APPLICATION OF THE AXIOMATIC DESIGN APPROACH TO THE DESIGN OF ARCHITECTURAL SYSTEMS: A LITERATURE REVIEW

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ABSTRACT

Architectural design has become increasingly complex due to the global environmental, energy issues, and socio-economic changes. Key parameters well considered in the early phase of the design process would provide good performance, competitive costs, and close-to-envisioned appearance of the built environment. Therefore, in order to reduce or minimize the complexity of the entire design process, a systematic approach is required, especially in the early phase of architectural design projects. While many systematic design approaches have been developed in engineering design, little effort has been made in architecture. Axiomatic Design (AD) is distinguished from other systematic design methods by having design axioms that guide good design decisions, especially in the early design phase. The AD approach has basic design principles which can be applied to problem analysis and decision-making. In this paper, a review and classification of AD applications in the architectural design processes is conducted. This study provides an initial framework which will be further developed to create a systemic framework to support architectural design in an efficient and effective way.

Keywords: architecture, Axiomatic Design, design principles.

1 INTRODUCTION

The complexity of architectural design is rising due to socio-economic changes, and environmental and energy issues. At the present time, the traditional decision models in construction project management are based on balancing cost, time, quality and sustainability. The goal of sustainability has become an important part of a holistic and simultaneous approach to overall building quality [BBSR, 2011]. Moreover the customer demands have become much more diverse and segmented, and each market segment requires specific design solutions. Architectural design has to satisfy specific customer's needs in order to improve customer satisfaction [Sabbadin, 2011]. Therefore the design of architectural systems has to be optimized with respect to a large number of different (sometimes conflicting) requirements and constraints, and the solution has to be selected from different available alternatives. The increasing complexity of architectural design entails the need for a more rational and systematic approach to the design process, especially in the conceptual design phase when decisions with fundamental and extensive effects on appearance, performance and costs are made [American Institute of Architects, 2007]. In this phase, most designers emphasize intuition and experience [Danke, 1979], which may not be adequate when the desired design solution is not easily found, the cost of failure is extremely high, the design task is extremely complicated, or when multiple stakeholders for the design are involved in the project. Conventional design methods are not suitable in many design projects due to complexity, high probability of errors and the requirement for team work [Cross, 2000]. Moreover the design process in architecture is not supported by a clear, integrated framework of available design supports [Chang, 2011].

Optimizing a design decision based on a varied and complex set of constraints requires an integrated and systematic approach, starting with the early phase of the design process which may include performing complex analyses, making decisions among conflicting parameters, and defining necessary compromises. In addition to conventional design methods, specific procedures are available. These methods, developed in engineering design, propose systematic approaches to the design activities, formalizing specific procedures and externalizing design thinking [Cross, 2000]. Although architectural design shares its framework with other design domains, like engineering design, rarely engineering design methods are applied in the architectural design process. AD is distinguished from other engineering design methods by the use of axioms that form a systematic and scientific basis for design decisions [Suh, 1990]. AD, developed by Nam P. Suh at MIT in engineering field, establishes that there are design principles that govern all good design decisions. It has been shown that this design theory can be applied to many different domains of problems including product design, systems design, large and small scale systems design, manufacturing process design and health care system design [Suh, 2001; Peck *et al.*, 2010]. It provides designers with a decision framework to evaluate the synthesized idea before and during the analytical phase, or to select good ideas from several plausible designs even in the very early design phase. AD allows the selection of the best alternative within a set of constraints, and also assures the most appropriate solution [Suh, 1990].

The AD approach has great potential in some non-engineering applications, such as architectural design. This study provides a literature review of these applications, and introduces a classification scheme based on application area, applied design phases and design activities, and applied methods and axioms. In the reviewed papers, AD has been mainly applied in the conceptual phase of the design process for addressing the design problems effectively towards specific goals. In most cases, the design problem is very specific, and usually concerns functional aspects. It is rare that an architectural design problem is studied as a multi-criteria decision making problem even though the fact that architectural design fulfils both practical and expressive requirements.

This study intends to analyse the applications of AD to the design of architectural systems, in order to improve the effectiveness of the decision-making process and to maintain the designed quality during the subsequent detail design processes. This analysis should contribute to the future development of a systems framework for the understanding and achievement of architectural design concepts in an efficient and effective way.

2 LITERATURE REVIEW

Architectural design is a process of creating synthesized solutions in the form of the built environment that fulfil both practical and expressive requirements according to existing constraints and available resources. Architectural design serves both utilitarian and aesthetic aims. They cannot be separated, but the relative weight given to each can vary widely. Therefore the characteristics of quality in a work of architecture consists of the suitability for the use by human beings and its adaptability to specific activities, the stability and permanence of the construction, and the aesthetic aspect through its form [Ackerman, 2013]. The required quality of architecture is constrained by finite resources (finance, time, resource, and whole-life value) [Dickson, 2004]. The traditional construction decision model, based on the balance among quality, time and cost, is nowadays widened involving the sustainability. Therefore the complexity of architectural design is increasing in an exponential way: architectural planning has to harmonize various demands in a utilitarian and aesthetic way within given socio-economic constraints.

Architectural design is an iterative and incremental process performed before the construction. In this process, an architectural product is identified (conceptual phase), defined (preliminary phase and develop phase) and specified (detailed phase) [UNI, 2007]. The architectural design process consists of multiple sub-processes through which various solutions are developed at different times, while the creation-evaluation-selection cycles for generating design solutions are constantly repeated during the entire process [Roozenburg and Cross, 1991]. In the architectural design process, design problem and solution co-evolve together along the process [Roozenburg and Cross, 1991], while the opportunity to influence the design decreases rapidly over time. In the early stage of the design process, architects elaborate potential solutions in order to obtain more information about problems from client. They use previous experiences and knowledge to define a simplified problem on the basis of which they later elaborate conjectures of possible solutions. Therefore, architects usually need to reformulate the design problem many times, while they keep track of all relevant issues of the specific design task [Danke, 1979]. In the early phase, there is a great potential to take decisions that are crucial on customer satisfaction, on performances and appearances of the design solution, and on reduction of project costs [American Institute of Architects, 2007]. In order to improve the effectiveness of the decision-making process in this phase, the team members have to agree on a common design strategy, that is a design process and design methods to follow, and on common goals [Macmillan *et al.*, 2001].

Traditional tools of design, such as design-by-drawing, cannot always adequately solve the current complex design tasks frequently imposed on designers [Cross, 2000]. An analysis of available architectural design tools shows that the design process in Architecture is not supported by a clear, integrated framework of design supports [Chang, 2011]. Moreover usually architectural design tools specialize in supporting late design development activities and relatively few have been developed to support the conceptual design phase [Wang, 2002]. Cavieres *et al.* [2011] retain that the lack of available conceptual design supports is due to the approach of architects to design in the conceptual design phase [Cavieres *et al.*, 2011]. Regarding sustainable building, a specific group of tools is available to evaluate different aspects of sustainability [Haapio and Viitaniemi, 2008] or to assess the overall building quality [BBSR, 2011]. Nevertheless these sustainable building assessment methods are designed to evaluate building projects at the later design stage, in order to provide an indication of the performances of buildings. They rely on detailed design information [Ding, 2008].

An analysis of existing design process models from both within and beyond construction was conducted by Macmillan *et al.*, [2001], in order to develop a generic framework of design activities for supporting building design in the conceptual phase [Macmillan *et al.*, 2001]. This study highlights some common features among existing design process models. Most describe a sequence of phases which, typically, imply iteration within phases, but not between one phase and another. Most set out only what should be undertaken, not why or how it should be performed. All the models start with an analysis of requirements, before the generation of possible solutions, showing progression. Most of the models imply convergence to one solution quite early in the design process, and only a few explicitly encourage the generation of alternative concepts for evaluation. None of the models makes explicit reference to ways for generating alternative solutions, or to formal measurement, evaluation or assessment methods [Macmillan *et al.*, 2001]. Moreover some differences emerge between architectural and engineering design approaches. Usually the architectural approach adopts solution-oriented models to design problems, generating solution concepts early in the design process through conjectures, followed by spiral and cyclic stages of descriptive procedures. Engineering approaches instead adopt problem-oriented models, focused on analysis of the problem, followed by prescriptive multi-phase procedures [Roozenburg and Cross, 1991]. These different approaches and the consequent lack of a shared understanding of the design process among the work team results in inefficient results [Macmillan *et al.*, 2001]. Suggestions for the development of common approaches are proposed by Blessing [1996] and Macmillan *et al.* [2001]. Blessing suggests merging solution-oriented and problem-oriented models. Macmillan *et al.* propose merging models focused on design solutions and models oriented to process management [Gericke and Blessing, 2012]. An integrated framework of phases and design activities for the conceptual building design phase is developed by Macmillan *et al.* [2001], based on a literature review, interviews and case study analyses, in order to guide the interdisciplinary work team to share common goals. This framework is composed of twelve activities in five phases, as shown in Table 1.

Table 1. Conceptual Building Design Framework [Macmillan *et al.*, 2001].

Stages	Phases	Activities
Develop business need into design strategy	Interpretation of needs	Specify business needs
		Assess stakeholder requirements
		Identify essential problems
	Developing of design parameters	Develop functional requirements
		Set key requirements
		Determine project characteristics
Develop design strategy into conceptual proposal	Divergent search	Search for solution principles
	Transformation of concepts	Transform and combine concepts
		Select suitable combinations
		Firm up into concept proposals
	Convergence to proposal	Evaluate and choose the proposal
		Improve details and cost of proposal

Usually in the early phase, many designers emphasize intuition and experience, but it is not often sufficient, especially when the design variables are numerous, and the context of application changes. Conventional design methods are not suitable in many design projects due to complexity, high probability of errors, and a lack of tools for team work. Architectural design needs systematic approaches to perform complex design analysis and knowledge integration, especially in the early stage of the design process, when decisions are made with fundamental and extensive effects on appearance, performance and costs. In addition to conventional design methods, specific procedures are available. These approaches, developed in engineering design, propose rational procedures of the design process, formalizing specific design methods and externalizing design thinking [Cross, 2000]. Designers may use and combine them to improve the effectiveness of the design process.

Although AD is one of these approaches, it is distinguished from the others because it guides the synthesis and decision-making process in developing design solutions through basic principles. It can be applied to all situations of solving design problems, from synthesis to analysis of the synthesized idea, then to select only good ideas from plausible solutions [Suh, 1990]. AD defines that the design process is the creation of synthesized solutions in the form of products, processes or systems, that satisfy perceived needs through interplay between functional requirements (FRs) and physical solutions expressed in terms of design parameters (DPs) at every hierarchical level of the process. This process continues moving down along the hierarchy until the designer produces an acceptable result. The design process is performed through design activities, and consists of four phases: problem definition, creative process, analytical process and ultimate check [Suh, 1990].

A comparison between the conceptual building design framework and the AD framework is conducted to relate them (Table 2).

Table 2. Design activities frameworks comparison.

Conceptual Building Design Framework [Macmillan *et al.*, 2001]	AD Framework [Suh, 1990]
Specify business needs	Identify needs
Assess stakeholder requirements	
Identify essential problems	
Develop functional requirements	Define a minimum set of functional requirements and determine constraints
Set key requirements	
Determine project characteristics	
Search for solution principles	Synthesize a physical solution characterized in term of design parameters
Transform and combine concepts	Analyse the solution. Eventually come up with a new idea or change the functional requirements
Select suitable combinations	
Firm up into concept proposals	
Evaluate and choose the proposal	Check the ultimate solution
Improve details and cost of proposal	

In AD, problem specification and solution are developed, starting by an analysis of needs, before the generation of possible solutions, in a gradual progression. During the design process, the formulation of the problem and ideas for a solution are developed together with constant shuttling to-and-from problem and solution (zig-zagging between what and how) in a top-down manner. The process starts with the specification of the first level of FRs in the functional domain and physical solutions (design parameters at the same level) have to be conceived that can satisfy FRs. The designer switches between functional and physical domains each time, moving down in the hierarchy and decomposing the upper-level of the FRs into lower-level. At each level of the functional domain only the most important FRs must be identified, eliminating secondary factors [Suh, 1990]. Architectural design in practice shows some similarities: it is an incremental process that has multiple sub-processes, while the creation-evaluation-selection cycle for generating design solutions is repeated during the process. On account of the previous considerations, AD may provide a suitable systematic framework for architectural design in the conceptual phase for addressing the design solution towards the demanded quality: it sets out what should be undertaken, and how it should be performed; it encourages the generation of alternative concepts, and indicates how to carry out the evaluation of alternative solutions.

An analysis of articles on AD applications to architectural design is conducted, and a classification is elaborated (Table 3 and Table 4). The reviewed articles are classified according to five main criteria: application area, design phase performed, methods proposed or applied and design activities performed, and finally the type of axiom adopted.

The *application area* column in Table 3 shows the major sectors of architectural applications and consists of five sub-sections: urban planning, building design, existing building improvement, construction project management and furniture design. The *design phase* column is created to highlight in which phase of the architectural design process the AD approach has been applied. The *methods* section intends to show how AD is utilized in each study to reach its objective. In this section, *application of AD* means that AD alone is applied in the study. *Application of integrated methods* states that the AD approach is utilized together with another method or methods in the study. *Theoretical development* explains whether the study proposes a theoretical improvement based on AD approach. The section *AD framework and methods* explains in detail the methods adopted or proposed in each design activity during the design process. The *axioms* section deals with the use of which kind of axiom in the paper: the first axiom (the Independent Axiom) and the second axiom (the Information Axiom).

Eliasson and Psilander [2000] intend to guarantee the achievement of customer satisfaction and profit required by home building industry through the application of specific methods. The ability of entrepreneurs in the home building industry is furnishing housing development for a chosen group of customers that places maximum value on the product offered. Competence Bloc Theory is used to relate customer preferences to the design process. A careful identification and definition of the customer is required. AD is introduced to focus on achieving the aesthetic quality and the maximum diversity of product quality with the minimum variability of inputs, in order to reach production process efficiency and customer satisfaction [Eliasson and Psilander, 2000].

Sohlenius [2000] presents a synthesis framework of a research proposal in terms of its aims, methods and phases regarding building industry and real-estate development. The goal is to maximize profitability in the construction industry in terms of income, cost and capital, by seeking a higher customer-value in both the short and long term and an effective building process. Since the building industry has many similarities with the manufacturing industry, the application of various manufacturing system design methods, such as AD, to the building process is discussed. Their research intends to understand the effectiveness of the design method regarding decision-making activities in the early stages of the design process. Qualitative Methods are proposed in combination with AD in a decision-making framework to facilitate the understanding of the customer requirements, especially according to aesthetic and social values [Sohlenius, 2000].

Table 3. Classification of literature review: application area and design phase.

	Application area					**Design phase**			
	Urban planning	**Building design**	**Existing building improvement**	**Project management**	**Furniture design**	**Conceptual**	**Preliminary**	**Developed**	**Detailed**
Eliasson *et al.* [2000]				housing development		√	-	-	-
Sohlenius [2000]				housing development		√	-	-	-
Helander *et al.* [2000]					seated workplace	√	-	-	-
Psilander [2002]		single-family house				√	-	-	-
Sohlenius *et al.* [2002]				housing development		√	-	-	-
Kowaltowski *et al.* [2003]	housing area development					√	-	-	-
Kankey and Ogot [2005]			acoustics of auditorium			-	√	-	-
Cavique *et al.* [2009]			energy efficiency of buildings			√	-	-	-
Pastor *et al.* [2011]		airport terminal				√	-	-	-

Table 4. Classification of literature review: methods, design activities and axioms.

	Methods			**AD framework and methods**					**Axioms**	
	Application of AD	**Application of integrated methods**	**Theoretical development**	**Problem definition**		**Creative process**	**Analytical process**	**Ultimate check**	**1**	**2**
				Recognition of needs	**Determination of FRs and Cs**	**Creation of solution in term of DPs**	**Analysis of solution**	**Check ultimate solution**		
Eliasson *et al.* [2000]			√	Competence Bloc Theory	AD	AD	-	-	√	-
Sohlenius [2000]			√	Qualitative Methods	AD	AD	-	-	√	-
Helander *et al.* [2000]	√			Literature review	AD	AD	AD	-	√	√
Psilander [2002]	√			Market analysis, Literature review	AD	AD	AD	-	√	-
Sohlenius *et al.* [2002]			√	Market analysis, Kano Model	AD, QFD, Robust Design, LOLA-rule	AD, TIPS	-	-	√	-
Kowaltowski *et al.* [2003]			√	Literature review, POE study	AD	AD	-	-	√	-
Kankey and Ogot [2005]		√		Literature review, EMS Model	AD, TRIZ	AD	AD	-	√	-
Cavique *et al.* [2009]	√			Literature review	AD	AD	AD	-	√	-
Pastor, *et al.* [2011]	√			Customer needs survey	AD	AD	AD	-	√	-

Helander *et al.* [2000] apply AD to improve the anthropometric design of a seated workplace. Using the Independence Axiom, an unconventional design solution is proposed. It results in a better solution than the conventional design solution recommended in the literature. The Information Axiom is introduced to select the best furniture available on the market. The selection is carried out based on the anthropometric data defined in the previous design phase. A significant improvement of the design methodology in ergonomics is possible with the specific features of AD. This approach proposes a clear framework: the analysis of the FRs through the design matrix, the evaluation of alternative designs by applying the Information Axiom, finally the identification of critical design parameters through the decomposition of the domains in hierarchical structures [Helander *et al.,* 2000].

Psilander [2002] applies AD to the design of dwellings in order to assure the correspondence between tastes of specific groups of customers and the realized project outcome. Their application concerns the conceptual design of a single-family house, using only qualitative information. The aim is to form an operative basis for making decisions about how the house can be realized, while maximizing profits and limiting costs. In order to maximize profits, the tastes of the target customer groups have to be guaranteed. The FRs of a dwelling are expressed in terms of function, quality and aesthetics. Appropriate DPs are indicated [Psilander, 2002]. Further, the highest level FRs and DPs are decomposed; for example the functionality is developed in terms of FRs and DPs to satisfy certain spatial relationships. With regard to the reduction of cost, standardization has been a known method. But some variety has to be guaranteed in order to go along with the customer's taste, and to provide identity. The possibility to combine architectural variations and standardized solutions depends on which types of standardized building materials and elements are used. Compared with an intuitive design process, the design process developed by AD allows rejecting bad project ideas even at the conceptual design stage. Moreover it allows identifying possible deviations during the process, determining where they appear and why they are made, and evaluating the consequences of deviations [Psilander, 2002].

Sohlenius and Johansson [2002] propose a framework based on AD combined with the Theory of Flexibility and LOLA-rule (LOw and LAte commitment) and other methods (Robust Design, Theory of Inventive Problem Solving and Quality Function Deployment) to improve the decision-making process in the conceptual design phase of the housing development process, and to achieve high customer value and high productivity. Meeting target customer's demand in the housing development means providing the satisfaction of the customer's requirements in an efficient way. Modularity can support the achievement of variation in order to satisfy different customer requirements efficiently [Sohlenius and Johansson, 2002]. An analysis of the context of a real estate development project (housing demand, housing supply site conditions, laws and regulations) is required to understand the market system, and to define needs and constraints. Proper specifications of a market analysis are necessary to allow an accurate quantification and identification of constraints and FRs. The Kano Model is proposed to structure the customer needs and to focus on the right quality. According to AD, FRs should be expressed with tolerances, but many architectural proprieties that are essential to achieve the overall quality of housing are non-measurable. In these cases, the profile for the real-estate development should be expressed clearly through an early market analysis. Constraints and FRs may change over time which cannot be foreseen. The Theory of Flexibility and the LOLA-rule are proposed for defining flexibility and limits of the design changes [Sohlenius and Johansson*,* 2002].

Kowaltowski *et al.* [2003] adopt AD to elaborate a systematic evaluation method regarding environmental impact and quality of life for the design of typical low-income housing, in order to improve the quality of future public housing design projects. This method should enable designers to consider a large number of factors that may interfere with the quality of user's life and the environmental sustainability. A literature review is elaborated to establish architectural and urban indicators that influence environmental and life quality for low income family housing projects [Kowaltowski *et al.*, 2003]. POE (Post Occupation Evaluation) method is proposed to verify if the selected indicators meet the perceived quality of life and the environmental quality by local population. The inclusion of people's perception of quality into the design process allows a direct link between design criteria and user desires. Therefore these indicators are included in the AD framework to rationalize, and to support the decision-making activity in the architectural design process. AD is able to include qualitative information in the design process, increasing the quality of the design solutions. Other analysis methods, such as simulation, checklist and multi-criteria optimization, are considered for the evaluation and the optimization of the design solutions, according to specific design parameters, especially regarding the aspects of comfort and energy efficiency [Kowaltowski *et al.*, 2003].

Kankey and Ogot [2005] investigate the use of AD combined with TRIZ to solve a problem of poor acoustics in a historical auditorium. The aim is the development of an affordable permanent solution that determines an enjoyable listening experience for most of the audience, and retains the historical aspect of the building. The Energy-Material-Signal (EMS) Model allows the designer to define the correct problem, decomposing and identifying scarce aspects (energy, material or signal flows) of the phenomena. FRs and DPs are defined and their couplings are shown. The result is a decoupled design. To obtain an uncoupled design according to the Independence Axiom, TRIZ is employed. Using AD to establish appropriate contradictions and TRIZ to come up with design solutions to overcome them, the solution results an uncoupled design [Kankey and Ogot, 2005].

Cavique *et al.* [2009] apply the AD approach to develop a framework to support the design of energy efficient heat, ventilation and air-conditioning (HVAC) systems. The energy consumption of HVAC systems depends on the characteristics of the building where the systems are installed. On account of this concept, the aim of the paper is to analyse both the reduction of energy consumption in a building and the decrease of energy consumption of the HVAC systems. Standards, directives and regulations are used to identify FRs and DPs. The mapping process of AD decomposes FRs and DPs in a general framework. The evaluation of the reduction of the energy consumption in the buildings considers the improvement of the performances of the building envelope, the reduction of internal loads and energy systems consumption and the local production of energy [Cavique *et al.*, 2009].

Pastor *et al.* [2011] test a new approach to the functional design problem of a passenger terminal in a small tourist airport applying the AD. The design of an airport passenger terminal requires the evaluation of an enormous number of variables. In the conceptual design phase, basic dimensions and infrastructures are defined based on specific formulas indicated by each national regulatory authority and international organizations, in order to guarantee a certain level of service and safety. Subsequently, distribution and configuration are determined according to architectural and functional criteria [Pastor *et al.*, 2011]. In this paper, the aim is to define a basic layout of the passenger terminal, using a minimal set of FRs. An analysis of the motion path following each passenger is conducted. Moreover an elaborated survey was conducted in order to establish a list of FRs of each functional area. A minimum set of FRs is selected following the Independent Axiom. This set represents the basic functions that each area should provide to guarantee customer satisfaction. The conceptual design of each functional area is defined individually, and the derived concept for the whole system is composed, linking optimally the sub-systems to each other. This study shows that a suitable selection of FRs and constraints allows the designer to define both dimensions and layout together and to determine a solution based on specific needs of different stakeholders [Pastor *et al.*, 2011].

3 DISCUSSION

This paper focuses on the early phase of the architectural design process, when decisions have the most effect on performance, appearance and the cost of the whole building project. This phase is not well understood and has been treated as an art. For design in practice, there has been little or no guidance on what should be done and how it should be achieved [Macmillan *et al.*, 1999]. A considerable amount of knowledge and experience from different disciplines and stakeholders are required to elaborate the problem description as well as the architect's intuitive imagination. These factors make it very difficult to develop an initial complete description of the architectural project, normally found in the scientific approach. Confusion often appears among the design team regarding the direction of progression, due to the lack of common goals. Moreover team members expect that all requirements can be satisfied equally without considering that some requirements often conflict [Macmillan *et al.*, 2001]. In this phase, architects usually use previous experiences and knowledge to define a simplified problem, in order to stimulate the conjecture of possible solutions, and they iteratively need to reformulate the design problem until problem and solution are defined explicitly. Therefore in architectural design, design problem and solution co-evolve together during the design process, while the opportunity to influence the design parameters decreases rapidly over time.

Although experience is important, it is often not sufficient, especially when the design variables are numerous, and the context of application changes. Experience should be supported by a systematic framework.

Many design studies show that designers supported by a systematic framework are better able to focus on the demands of a problem than those without a framework [Archer, 1984]. A framework of design activities developed by Macmillan *et al.* [2001] for the conceptual building design phase is available, in order to support interdisciplinary teamwork through the promotion of collaborative design development. This framework may form the basis on which systematic design methods are embedded, in order to evaluate their effectiveness in the decision-making activity.

The AD approach, a systematic design method, proposes to support the development of good design solutions through basic principles of functional independence and complexity minimization. This approach demands a clear formulation of the design problem: it states that, in order to generate good design satisfying specific needs and required quality, designers must define the design goals in terms of "what they want to achieve" and provide a clear description of "how to achieve it" [Suh, 2001].

An assessment of the literature review regarding applications of AD to the design of architectural systems is provided, and a classification scheme is introduced based on the application area, performed design phase and design activities, applied methods and axioms. The number of papers on this topic is not high. This analysis takes in account papers elaborated on applications of AD in architectural design between the years of 2000 and 2011. Unfortunately there are certain limitations: studies published in academic journals outside of databases and non-English papers have not been included. Both practical and theoretical papers are evaluated and classified.

As regards practical articles, AD has been used to support the definition of solutions for specific design problems. The application of AD covers various fields and built-in structures such as: housing development, customization of dwellings in the building industry, functional design of a small passenger terminal airport, acoustic improvement of a historic building, increase of the energy efficiency performances of the building envelope and improvement of anthropometric design of a seated workplace. In these cases, the design problem is very specific, and mainly concerns functional aspects. Although architectural design fulfils both utilitarian and aesthetic requirements, it is rare that the aesthetic aspect of architectural design problem is considered as a multi-criteria decision making problem. In one case, functional, constructional and aesthetic aspects of the design problem are evaluated together [Psilander, 2002]. The field of furniture design can also benefit by the AD approach, which has been widely used in the production design area.

Theoretical articles pertain to studies which allow theoretical developments in specific fields through the use of the AD approach. In particular, AD is proposed to support the project management activity for ensuring the correspondence between needs of customers and realized projects. In the reviewed papers, AD is mainly applied in the conceptual design phase to address the design process effectively towards specified goals. In most studies, the AD approach is applied alone without the contribution of other methods. In one case, AD is integrated with other methods, such as TRIZ, to solve contradictions. Moreover different specific methods are proposed for the definition of the design problem.

In most articles, the first axiom is generally applied. It is widely used since it permits the designer to reduce random research processes, and to minimize the repeated trial-and-error-activities [Kulak *et al.*, 2010]. The second axiom is rarely used in these applications. In general, the Information Axiom is applied on multi-criteria decision making problems and for the selection of the most appropriate alternative within specific criteria [Kulak *et al.*, 2010]. In the analysed applications, the design problem is usually very specific. Moreover rarely different alternative solutions are proposed and evaluated.

4 CONCLUSIONS

Design research on the architectural design process underlines that this process has a hierarchical structure in which the formulation of the problem and the development of the solution evolve together in a cyclic sequence during the process. The design problem escapes an initial complete definition since it requires a considerable amount of knowledge from different disciplines and stakeholders. Therefore usually designers use their knowledge and past experience to formulate a simplified problem and to stimulate a solution-conjecture based on it.

In AD, the problem specification and the solution are developed in a gradual progression starting by an analysis of needs, before the generation of possible solutions and with top-down and to-and-from navigation between problem (FRs) and solution (DPs). A clear formulation of the design problem is required: the design goals must be defined and a clear description of related design parameters must be provided.

This study identifies that in the majority of the published applications of AD to architecture, AD is used for solving specific design problems. We believe, however, that AD can support the designer's experience by providing a logical and rational thought process when the design variables are numerous and the context of application changes. Therefore AD needs to be further studied in the early phase of architectural design applications that intend to consider the various FRs, DPs and constraints of architectural design projects.

This article intends to form the basis for the future development of a systems framework that improves the effectiveness and the efficiency of the conceptual design process in architectural design. An existing framework of design activities that supports and aids the interdisciplinary team towards common goals can be adopted and integrated to the AD framework.

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