



Review

Applications of axiomatic design principles: A literature review

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ABSTRACT

Although there have been quite a number of theoretical and practical studies where axiomatic design (AD) principles have been used in the last few years, there is a lack of a comprehensive literature survey which evaluates and classifies these papers. This study provides a recognizable overview of literature on AD principles from the past 20 years and introduces a novel classification scheme covering 63 papers. Each article was classified into four main groups, namely the type of the axiom, the application area, the method, and the evaluation type. Findings of our paper indicate that most of the studies in the literature are application-based papers which use typically the independence axiom. While product design is put forward in the application area, the crisp approach is widely used as an evaluation type. A rise in the fuzzy evaluation based research studies using the information axiom for multi-attribute decision making problems has also been noticed.

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1. Introduction

Today's competition conditions have carried customer needs to an effective position in all decisions related to service and production systems. There are a wide range of customer needs affecting decision makers in many decisions on product design and system design to find the most appropriate alternatives. Many new models which predicate on AD principles have been developed in the last few years to include these needs within the decision-making process with a systematic approach and to present comprehensive solution suggestions to decision makers.

Axioms are general principles which are evident actualities that cannot be proven to be correct but which do not have counter examples (Suh, 1990). AD principles developed by Suh (1990) to form systematic scientific basis for designers, especially in the design processes of product, production systems, and software design are widely used to solve many design problems. These principles present better design solutions in the shortest time as they provide a systematic research process in a design space which becomes complicated with customer needs. In addition, the fact that axioms can be generalized allows this method to be effective and powerful in different design areas.

In the last few years, new studies aiming at solving multi-criteria decision making problems based on AD principles have been presented. AD principles, which allow for the selection of not only the best alternative within a set of criteria but also the most appro-

priate alternative, show a great difference when compared with other approaches. Additionally, AD principles also have differences in comparison with other methods due to the way that they can evaluate design alternatives with respect to the criteria including both crisp and fuzzy values in a multi-criteria decision making problem. The number of studies using AD principles is gradually increasing as AD's superiorities create important advantages for decision makers in solving multi-criteria decision making problems.

Although there have been quite a number of theoretical and practical studies where AD principles have been used in the last few years, a comprehensive literature survey which evaluates and classifies them does not exist. In this paper, the studies using AD principles have been classified with respect to *the axioms they use, the type of evaluation, their application areas, and their theoretical contents* for the first time in literature. The reasons for their widespread usage have been researched within the extent of this study.

The rest of the paper is organized as in the following. In Section 2, axiomatic design and its principles are presented. Then the classification of applications on AD principles with a literature review is given in Section 3. Finally, the concluding remarks are presented in Section 4.

2. Axiomatic design and its principles

Axioms are widely accepted principles which are the fundamental concepts of this process. The first design axiom is known

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as the Independence Axiom and the second axiom is known as the Information Axiom. They are stated as follows (Suh, 1990).

Axiom 1. The Independence Axiom: Maintain the independence of functional requirements.

Axiom 2. The Information Axiom: Minimize the information content.

The Independence Axiom states that the independence of functional requirements (FRs) must always be maintained, where FRs are defined as the minimum set of independent requirements that characterizes the design goals. Mathematically, the relationship between the FRs and DPs are expressed as

$$\{\mathbf{FR}\} = \mathbf{A}\{\mathbf{DP}\}.$$

Here,

- {FR} is the functional requirement vector;
- {DP} is the design parameter vector; and
- |A| is the design matrix that characterizes the design.

In general each entry a_{ij} of **A** relates the i th FR to the j th DP.

The structure of |A| matrix defines the type of design being considered. In order to satisfy the independence axiom, |A| matrix should have an uncoupled or decoupled design.

The Information Axiom states that among those designs that satisfy the Independence Axiom, the design that has the smallest information content is the best design. Information is defined in terms of the information content, I_i , that is related in its simplest form to the probability of satisfying the given FRs. Information content I_i for a given FR_i is defined as follows:

$$I_i = \log_2\left(\frac{1}{p_i}\right), \tag{1}$$

where p_i is the probability of achieving the functional requirement FR_i and log is either the logarithm in base 2 (with the unit of bits).

In any design situation, the probability of success is given by what the designer wishes to achieve in terms of tolerance (i.e. design range) and what the system is capable of delivering (i.e. system range). As shown in Fig. 1, the overlap between the designer-specified “design range” and the system capability range “system range” is the region where the acceptable solution exists. Therefore, in the case of uniform probability distribution function p_i may be written as

$$p_i = \left(\frac{\text{Common range}}{\text{System range}}\right). \tag{2}$$

Therefore, the information content is equal to

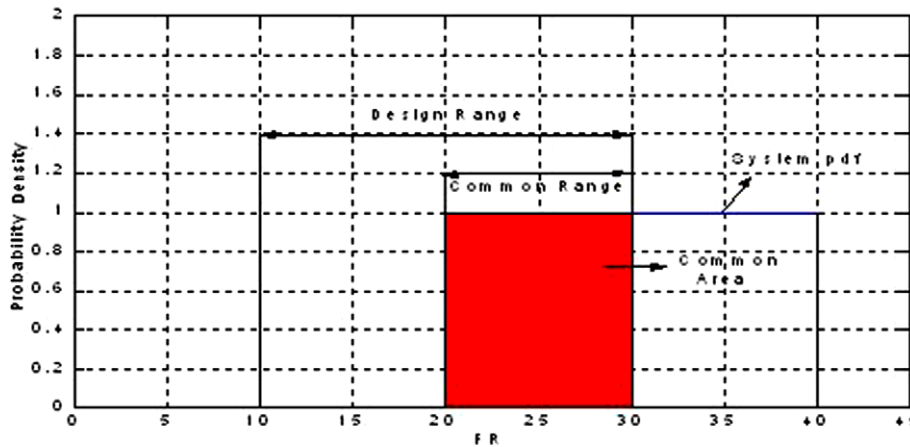


Fig. 1. Design, system, common range and probability density function of a FR.

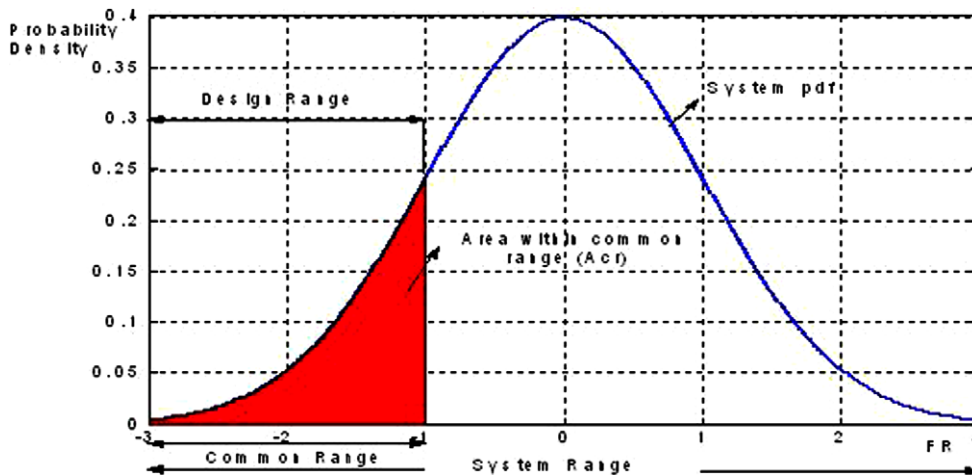


Fig. 2. Design, system, common range and probability density function of a FR.

$$I_i = \log_2 \left(\frac{\text{System range}}{\text{Common range}} \right). \tag{3}$$

The probability of achieving FR_i in the design range may be expressed, if FR_i is a continuous random variable, as

$$p_i = \int_{dr^l}^{dr^u} p_s(FR_i) \cdot dFR_i, \tag{4}$$

where $p_s(FR_i)$ is the system pdf (probability density function) for FR_i . Eq. (4) gives the probability of success by integrating the system pdf over the entire design range. (i.e. the lower bound of design range, dr^l , to the upper bound of the design range, dr^u). In Fig. 2, the area of the common range (A_{cr}) is equal to the probability of success p_i .

Therefore, the information content is equal to

$$I = \log_2 \left(\frac{1}{A_{cr}} \right). \tag{5}$$

The Fuzzy Information Axiom has been developed by Kulak and Kahraman (2005a, 2005b) to solve Multi-Attribute decision making problems having linguistic information. The crisp IA approach explained above can be used as the solution of decision-making problems where available information is suitable to be modelled by probability theory. However, this approach cannot be used where available information is qualitative and linguistic. Fuzzy set theory is very helpful to deal with the kind of vagueness of human thought and language in decision making. Due to its simplicity and ease of implementation, the notation of triangular fuzzy number is formulated below (Eq. (6)) and depicted in Fig. 3.

$$\mu(x) = \begin{cases} \frac{x-c}{a-c}, & c \leq x \leq a, \\ \frac{b-x}{b-a}, & a \leq x \leq b, \\ 0, & \text{otherwise.} \end{cases} \tag{6}$$

If the system and design ranges data are expressed linguistically, an imprecise information situation arises in IA. In this case, the system and design ranges data are linguistic terms which are expressed with fuzzy numbers (i.e., triangular or trapezoidal fuzzy number-TFN). So, the common area is the intersection area of the system's TFN and the design's TFN (Fig. 4).

Therefore, the information content in the fuzzy case is equal to

$$I = \log_2 \left(\frac{\text{TFN of system range}}{\text{common area}} \right). \tag{7}$$

3. Literature review of axiomatic design principles

In this study, the articles including axiomatic design approaches have been analyzed. As it is shown in Table 1, the articles are classified into four main groups; (1) *type of axiom*, (2) *application area*, (3) *method*, and (4) *evaluation type*. *Type of axiom* states two axioms of axiomatic design principles: independence axiom and information axiom. *Application area* is created to show the main purpose of the used AD approach. Hence, this section consists of six subsections; (1) product design, (2) system design, (3) manufacturing system design, (4) software design, (5) decision making, and (6) others. Each section will be explained in the rest of the paper. The *method* section of Table 1 is created to highlight how AD

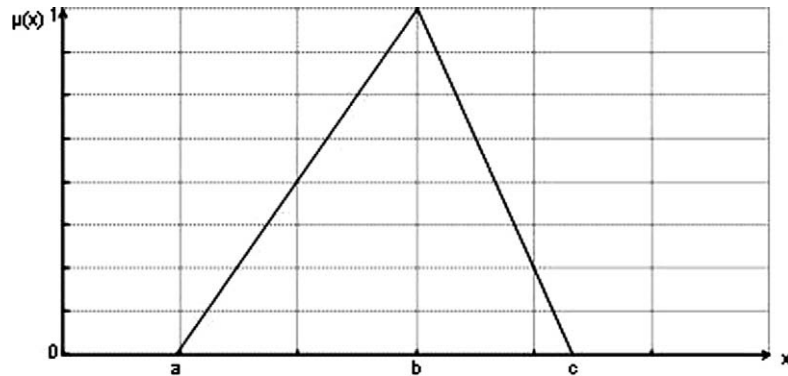


Fig. 3. Triangular fuzzy number.

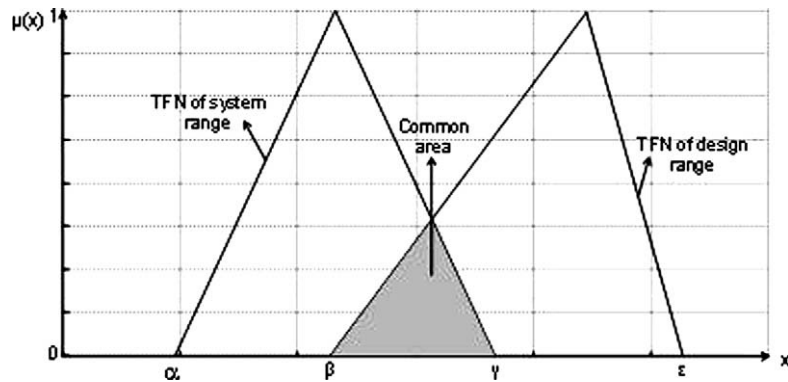


Fig. 4. The common area of system and design ranges.

Table 1
Classification of literature review (the years between 1990 and 2009).

	Axiom		Application area						Method			Type of evaluation	
	Independence	Information	Product design	System design	Manufacturing system design	Software design	Decision making	Others	An application of AD	An integrated method	Theoretical development	Crisp	Fuzzy
Suh (1990)	✓	✓	✓						✓			✓	
Kim et al. (1991)	✓								✓			✓	
Gunasekera and Ali (1995)	✓								✓			✓	
Suh (1995a)	✓			✓					✓		✓	✓	
Suh (1995b)	✓		✓						✓		✓	✓	
Harutunian et al. (1996)	✓								✓			✓	
Gazdik (1996)	✓		✓							✓		✓	✓
Suh (1997)	✓			✓					✓			✓	
Tseng and Jiao (1997)	✓		✓						✓	✓		✓	
Suh et al. (1998)	✓				✓				✓			✓	
Goel and ve Singh (1998)	✓	✓	✓					✓	✓			✓	
Cha and ve Cho (1999)	✓		✓						✓			✓	
Cochran et al. (2000)	✓				✓				✓			✓	
Suh and Do (2000)	✓								✓	✓		✓	
Chen et al. (2001)	✓								✓			✓	
Donnarumma et al. (2002)	✓	✓							✓		✓	✓	
Bae et al. (2002)	✓		✓						✓			✓	
Huang (2002)	✓								✓		✓	✓	
Jang et al. (2002)	✓	✓	✓						✓			✓	
Huang and Jiang (2002)	✓								✓		✓	✓	✓
Melvin and Suh (2002)	✓								✓	✓		✓	
Lee et al. (2003)	✓		✓						✓		✓	✓	
Kim et al. (2003)	✓		✓						✓			✓	
Su et al. (2003)	✓								✓			✓	
Chen et al. (2003)	✓								✓			✓	
Lindkvist and Söderberk (2003)	✓		✓						✓		✓	✓	
Deo and Suh (2004)	✓			✓					✓		✓	✓	
Chen and Feng (2004)	✓		✓						✓			✓	
Ngai and Jiao (2004)	✓								✓		✓	✓	
Suh (2005)	✓							✓	✓		✓	✓	
Thielman et al. (2005)	✓			✓					✓			✓	
Hirani and ve Suh (2005)	✓		✓						✓			✓	

Yi and Park (2005)	✓				✓			✓												
Kulak, Durmusoglu, and Tufekci (2005) and Kulak, Durmusoglu, and Kahraman (2005)	✓				✓			✓												
Kulak (2005)		✓																		
Pappalardo and Naddeo (2005)	✓																			✓
Kulak and Kahraman (2005a)		✓																		✓
Kulak and Kahraman (2005b)		✓																		✓
Houshmand and Jamshidnezhad (2006)	✓																			✓
Thielman and Ge (2006)	✓																			✓
Heo and Lee (2007)	✓																			✓
Liang (2007)	✓																			✓
Schnetzler et al. (2007)	✓																			✓
Nakao et al. (2007)	✓																			✓
Coelho and Mourão (2007)	✓																			✓
Helander (2007)	✓																			✓
Lo and Helander (2007)	✓																			✓
Bang and Heo (2009)	✓																			✓
Shin et al. (2008)	✓																			✓
Ferrer et al. (2009)	✓																			✓
Togay et al. (2008)	✓																			✓
Lee and Shin (2008)	✓																			✓
Durmusoglu and Kulak (2008)	✓																			✓
Gumus et al. (2008)	✓																			✓
Tang et al. (2009)	✓																			✓
Kahraman and Cebi (2009)		✓																		✓
Celik, Kahraman, et al. (2009)		✓																		✓
Celik, Cebi, et al. (2009a)		✓																		✓
Celik, Cebi, et al. (2009b)		✓																		✓
Celik (2009a)		✓																		✓
Celik (2009b)		✓																		✓
Celik (2009c)		✓																		✓

principles are utilized in the corresponding study to reach its aim. Under this title, *An application of AD* means the area where AD approaches is used in the study. *Integrated method* states that AD approach is utilized together with another method or methods in the corresponding study. *Theoretical development* explains that a new theoretical method based on an AD approach has been developed. The last section, *type of evaluation*, explains the type of assessments

between functional requirements and design parameters or alternatives.

The following graphical illustrations can be obtained from Table 1. Fig. 5 shows the discrimination with respect to the used axioms in the papers.

Fig. 6 illustrates the application areas of AD in the literature.

Fig. 7 depicts the type of evaluation sets: crisp or fuzzy.

Fig. 8 presents the frequency-years graphic of the papers published between the years 1990 and 2009.

3.1. System design

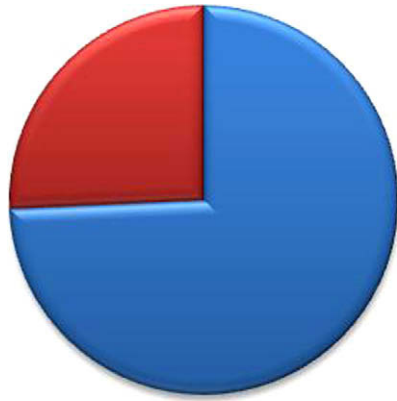
A system design is a process of defining the architecture, components, modules, interfaces, and data in order to satisfy the defined requirements. In the literature, the articles that have been proposed for the design of a system based on AD principles are summarized as follows;

Suh (1995a) proposed a conceptual framework for the design of a large system based on axiomatic design methodology. According to this AD methodology, a large system was defined as a system which had to satisfy various sets of functional requirements over the system's lifetime such that some of them were not predicted before. In the study, several theorems were presented based on independence and information axioms for the design of large systems. The details of the proposed theorems were examined in the design process of organizations and intelligent manufacturing systems.

In another study, Suh (1997) presented the identification and classification of the systems and suggested conceptual design proposals in order to design systems. In this study, systems were classified as large and small systems according to the number of their functional requirements. While small systems were defined as systems which did not change as a function of time and had to satisfy a limited and fixed set of functional requirements, large systems were expressed as systems which had a large number of functional requirements at the highest specification level. The AD approach was recommended as an alternative method for the design of systems instead of know-how and trial-and-error methods. In the study, improving the performance of a system was realized by increasing the quality of the design based on the independence axiom.

Bae, Lee, and ve Chu (2002) presented the sequential kinematic design of a suspension system based on axiomatic design principles. In the study, independence axiom was used to define relationships between hard points and suspension geometries and to improve suspension system design. Since it was aimed to reach the ideal design by determining dominant DPs, two methods – grouping the effective DPs and freezing the unnecessary DPs – were combined in the study. In the case study, the method was applied in order to compare the current design configurations of three typical suspension systems which are the McPherson strut, double wishbone, and multilink design.

Thielman, Ge, Wub, and Parme (2005) proposed an approach based on axiomatic design methodology in order to construct a model including both quantitative and qualitative tools. The proposed methodology consisted of five steps; (1) decomposition of the system into FRs, DPs, and design matrices, (2) characterizing the system with analytical and numerical models, (3) populating the design matrix, (4) evaluating the system based on reangularity and semangularity, and (5) improving systems using an optimization model. The zigzag design process was used to decompose the system and the independence axiom was used to represent the relations. In the proposed approach, the optimization model was developed based on reangularity and semangularity definition in order to minimize the degree of coupling of the design. The proposed approach is applied to evaluate and optimize the reactor



■ Independence Axiom ■ Information Axiom

Fig. 5. Discrimination with respect to axioms.

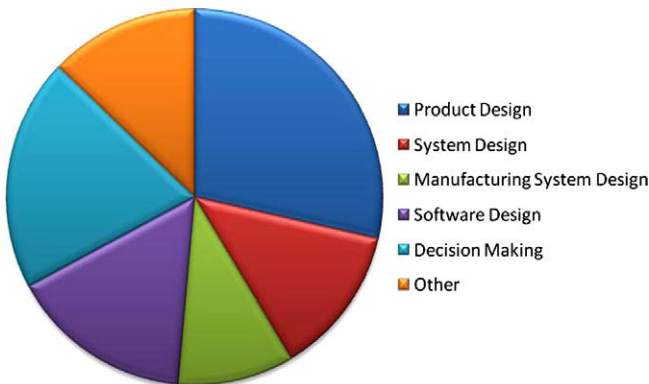
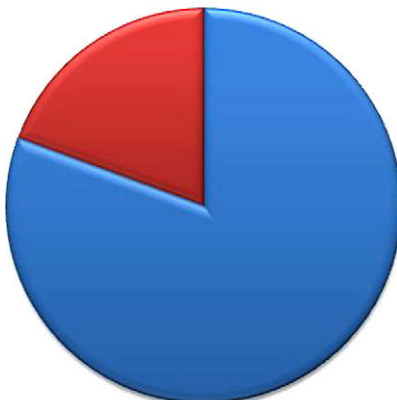


Fig. 6. Application areas of AD.



■ Crisp ■ Fuzzy

Fig. 7. Type of evaluation sets.

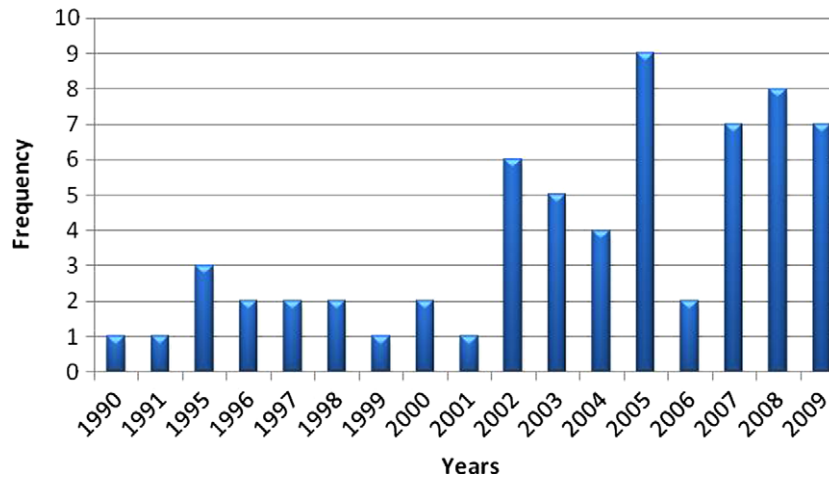


Fig. 8. The frequency-years graphic.

cavity cooling system of General Atomics' Gas Turbine-Modular Helium Reactor.

Thielman and Ge (2006) proposed a systematic methodology based on axiomatic design principles in order to evaluate and optimize large scale engineering systems. First of all, functional requirements and design parameters are obtained using the independence axiom at different hierarchical levels of a system. Then an analysis was conducted based on the ratio obtained from renagularity (R) and semangularity (S) definition in order to evaluate the existing system design. It was recommended to use an R/S optimization to achieve a less functionally coupled design when the design was coupled according to R/S analysis. The proposed approach was applied to a nuclear reactor system design.

Heo and Lee (2007) examined the design process of emergency core cooling systems in nuclear power plants by using independence axiom. In the presented study, the independence axiom was used as a measure to improve nuclear safety. In designing the safety features of nuclear power plants, the axiom was used to explain the different responsibilities of the design strategies such as independency or redundancy. In the study, two current emergency core cooling systems, OPR1000 (Optimized Power Reactor 1000MWe) and APR1400 (Advanced Power Reactor 14000MWe) were investigated based on the independence axiom with respect to the defined FRs and DPs. Subsequently, the best design was determined in accordance with the independence and redundancy,

Helander (2007) proposed an approach, called design equations, for system analysis based axiomatic design. The purpose of the paper was to identify sources of couplings and propose new design parameters that uncouple the design for human factors design. In the study, both axioms of axiomatic design principles were used. The independence axiom was used to reduce couplings and complexity in human machine interaction. The information axiom was applied to human factor design in order to take into account the variability of human attributes. As the case studies, a refrigerator, hand tools and a driver's compartment were taken into account by the independence axiom while the information axiom was illustrated by an adjustable workstation.

Bang and Heo (2009) presented a new design of coolant nanofluids as a coolant of a thermal fluid system based on independence axiom. The design of nanofluid system was coupled due to the characteristics of the thermal-fluid system. In the system, the independence axiom was used to eliminate the degree of coupling of

the system as it was seen that the design parameters affected each other.

3.2. Product design

Product design is to design new products which have good advantages with respect to aesthetics, functionality, ergonomics, material, marketability, and production methods and opportunities in order to meet customer requirements. The examples of AD approach for product design are given in the following;

Suh (1990) presented a conceptual design model for the design of the machines revealing creative designs by using the AD approach. The thinking-design machine was defined as the machine which had the ability of accurate decision-making and a rich data base in order to synthesize creative designs. The developed model involved four steps for the design of machines; (1) the definition of functional requirements, (2) the creation of design parameters, (3) the analysis of design solution, and (4) the control of the final solution. While the analysis of the proposed design solutions was based on the independence axiom, the information axiom was recommended for the selection of the appropriate design alternatives.

Suh (1995b) proposed a conceptual method in order to make decisions during the design stage of product and process development affecting product quality and process productivity. To improve quality, the proposed method requires for statistical process to control and for other methodologies to be consistent with the independence and information axioms. In the study, several design criteria were derived and discussed based on the independence axiom and some theorems in order to control the quality of products were developed. These criteria limited the validity of some of the quality control techniques. Additionally, the information axiom was recommended to make the selection of the best design when there was more than one acceptable design of a product or process.

Gazdik (1996) reviewed the usability of Zadeh's Extension Principle to analyze the design of system based on independence axiom since the groups and the environment in which the system operated were fuzzy. A real life example was presented to illustrate the applicability of the method.

Tseng and Jiao (1997) proposed a modular electrical design of electronic products at the system design level based on independence axiom in order to solve problems of definition and creation of modules during the design of the electronic product. The proposed method was applied to the design of electronic power

supply product since it contained multi-disciplinary exploration. The difficulty of determining modules of a product was related to the design matrix which did not satisfy the independence axiom. In the study, Rank Order Clustering was used in order to transform coupled design into uncoupled or decoupled design. As a result of the use of this method, the functional requirements and design parameters were collected in the same group to create modules.

Goel and ve Singh (1998) proposed a framework for durable product design at the conceptual stage of product development by integrating creativity and innovation aspects with the principles of AD. In the study, various creativity and innovation methodologies were discussed. The following five steps; information collection and analysis, defining scope and requirements, selection and development of the concept, design details and optimization, and validation and verification, defined the proposed product development process. The proposed method for product design was finally integrated by axiomatic design principles. Both the independence and information axioms were recommended to be used in the implementation phase of the method.

Cha and ve Cho (1999) used the independence axiom in order to analyze and improve the performance of the current design of a DVD. The functional requirements and related design parameters were determined on the basis of the independence axiom.

Jang, Yang, Song, Yeun, and Do (2002) presented an application of axiomatic design principles in marine design problems. In the study, four case studies that were of a conceptual thruster design, a foil-strut optimization problem, a main engine selection problem, and a barge design problem were taken into consideration. In the first case study, the independence axiom was used to illustrate the conceptual design of a thrusters'. In the second case, the usability of the information axiom in the optimization of design variables was illustrated for the foil-strut example satisfying the independence axiom. In the third case, the information axiom was used as a selection tool for the main engine selection problem. In the last case, information axiom was used for rating the design parameters while independence axiom was used for the selection of design parameters for the barge design based on the reangularity and semangularity definitions.

Kim, Chung, and Cha (2003) presented a tribological design in order to minimize the surface damage of head/disk interface based on the first axiom of the axiomatic design approach. In their study, the design parameters of tribological behaviour of the head/disk interface were investigated with respect to the functional requirements of the head/disk interface for minimum surface damage.

Lee, Seo, and Park (2003) proposed a redesigning procedure for automobile subframes based on finite element analysis and the independence axiom. In the study, a program that automatically increased the thickness of the materials based on finite element analysis was developed. The independence axiom was used to determine the optimal thickness of each subpart-shell. Functional requirements were defined to relieve maximum stresses and design parameters were defined by a set of thickness of each panel.

Hirani and ve Suh (2005) presented an optimum design methodology for fluid film steadily loaded journal bearings in order to improve operating characteristics. The proposed methodology consisted of an analytical approach, a finite difference mass conserving algorithm, a genetic algorithm, and the independence axiom. The independence axiom was used to eliminate redundancy and coupling problems in journal bearing design.

Liang (2007) applied axiomatic design principles to icon design process. The aim of the study was to overcome the deficiency of a trial-and-error process which is time-consuming and costly. For this purpose, the method was used to analyze and evaluate the visual distinctiveness of icons and the appropriateness of representation. While the independence axiom was used to analyze the discrimination of icons, the information axiom was used to mea-

sure associations between the visual features of icons and their referent concepts. The designs of icons in process control displays were illustrated by using axiomatic design principles in the study.

Lo and Helander (2007) developed a method based on the axiomatic design to identify couplings and to suggest advice for eliminating couplings. The model constructed the following domains: the goal domain, the functional domain, the physical domain, and the action domain. The mappings between the proposed domains were presented by using design equations. The proposed approach was applied to the design of adjustable microscope workstation, design of manual single-lens-reflex camera, design of manual point-and-shoot film camera, and design of dual reservoir system.

Ferrer, Rios, and Ciur (2009) proposed a two-phase approach based on axiomatic design methodology in order to make a connection between design and manufacturing information. In the first phase, the independence axiom was used to define and formalize the design parameters which satisfied FRs and design constraints. In the second phase, the essential manufacturing process information was defined and formalized. The manufacturing information was represented by the concepts of process property and process execution variable. In the second phase, manufacturing process selection was implemented; and then, process variables and execution variables were defined and formalized. The proposed approach was applied to a connecting rod design, an internal combustion engine part.

Gumus, Ertas, Tate, and Cicek (2008) developed a product development lifecycle model based on the independence axiom and design domains. The aim of the study was to develop, capture, and present both the schematic structure and a detailed view of the product development knowledge. The main difference between the proposed method and the conventional AD method is that the proposed method includes test domain over the four domains presented by AD.

Lee and Shin (2008) developed a product design method based on the independence axiom in order to develop the design of water jet nozzle for cleaning TFT and LCD screens. A number of FRs were determined in order to maximize the cleaning effect and the decoupled design was developed between FRs and DPs based on the independence axiom. In the study, it was mentioned that axiomatic design with the design of experiments was efficient since it did not require any mathematical formulation of design problem.

Shin, Lee, Lee, Song, and Park (2008) proposed a nuclear fuel spacer grid design, a part of the fuel system, using independence axiom and optimization. The independence axiom was used to define the design areas. In the study, the FRs and DPs were determined for the spacer grid design and it was shown that the design matrix was uncoupled. Therefore, the design parameters were taken into consideration separately. Then, the formulation for optimization was defined using the constraints in the design area for each design parameter.

Tang, Zhang, and Dai (2009) analyzed the disadvantages of axiomatic design and design structure matrix (DSM), which were two popular design methods and proposed an integrated approach to combine the strengths of the methodologies. The independence axiom of the axiomatic design principles guided the designer finding suitable design parameters to meet the needs of function requirements. However, axiomatic design did not support the designer to know the interactions among the design parameters, including geometry, spatial layout, and interfaces. The design structure matrix had the advantages in recording and analyzing the interaction relationship between existing product elements. Nevertheless, at the conceptual design stage of a new product that had never been designed before, it was difficult to make the design structure matrix. Therefore, an

integrated approach was presented to overcome the deficiencies of the methodologies in the study. A conceptual design example of chocolate wrapping mechanism was given to illustrate the power of integration between AD and DSM.

3.3. Software design

Software design is defined as a process of problem solving and planning for a software solution. The first step for software design is to define the aim and characteristics of the software. Then, in the next step, the software is developed based on a plan for a solution. In this subsection, the papers including software whose framework is created based on axiomatic design principles are taken into consideration. These studies are as follows.

Based on the axiomatic design principles, Kim, Suh, and Kim (1991) developed a conceptual model in order to increase the reliability and usability of the software required for any kind of computers. A systematic model was proposed to minimize the problems in the software design and to meet customer requirements using the independence axiom. Two software examples were presented to illustrate the usability of independence axiom in software design. The first one was the library software which implemented functions such as updating database, finding the desired book, etc. The other was the software belonging to a system that formed plastic parts by injection.

Gunasekera and Ali (1995) proposed an approach which consisted of an initial design and final design stages in order to develop a process design of metal forming. The independence axiom of axiomatic design principles was selected since it was a powerful tool to realize a conceptual design. The developed method provided a powerful solution to reduce the time and usage of resources of a metal forming process.

Harutunian, Nordlund, Tate, and Suh (1996) developed a software tool based on axiomatic design in order to improve the engineering CAD environment through the documentation of design rational. The independence axiom of the AD principles was implemented to evaluate design decisions and provide the proper development sequence.

Suh and Do (2000) proposed an approach combining object-oriented programming and the independence axiom in order to design large software systems. The use of AD provided the benefits such as shortening the lead-time of software, reliability, low cost, and high productivity. In the study, commercial software was developed by the proposed approach.

Chen, Chen, and Lin (2001) developed a knowledge-based system using simulation method in order to increase the performance of the manufacturing cells. The independence axiom was used to build a hierarchical knowledge base corresponding decision process. A simulation model was constructed and combined with decision support system in order to illustrate the effectiveness of the proposed knowledge base system. As the result of execution of the simulation model, it easily found the bottleneck sources in the cell and provided recommendations for solving the problems.

Huang (2002) proposed an approach based on extension of the axiomatic design principles. In the proposed methodology, two master domains were defined: design workspace and review workspace. A designer or a designer team presented the proposed design in design workspace and inspected it based on the review methods or theories. Each master domain included three domains. While design review workspace consisted of design requirements, design constraints, and design parameter, the review workspace consisted of design capability and some parameters and review criteria. The relations between each sub-domain were investigated based on the independence axiom. The proposed design approach was named as systematic theory of axiomatic design review. The

software called *cyber review* was developed based on the proposed method. The proposed methodology was illustrated by a push scooter design.

Huang and Jiang (2002) extended the proposed methodology into the fuzzy set theory where fuzzy numbers and fuzzy set operations were extensively used during the design review process. The past experiences and insights were expressed as the membership functions of design parameters and evaluation criteria. Then the extended fuzzy method was applied to fuel pump design.

Lindkvist and Söderberk (2003) proposed a methodology and developed a software tool to evaluate and analyze the design of assemblies with respect to degree of geometrical coupling and robustness. For this purpose, the robust design and independence axiom of axiomatic design were used to compare and evaluate assembly concept solutions. The developed software implemented the tolerance chain and stability analysis. The proposed approach was applied to two different vehicle floor concepts and to a small combustion engine in order to present its usability.

Chen, Feng, and Zhang (2003) developed a framework of computer-aided quotation system including five models using Axiomatic Design. The use of the independence axiom facilitated both the integration of existing software and the modification of software since changes in one module did not affect other modules and many functions. According to the framework, computer-aided quotation systems were developed and applied to modular machine tools, combined cold storage, and acid-resistant pumps.

Chen and Feng (2004) proposed a modelling method in order to implement via applying the function of CAD graphic software and built the model including material information such as periodic microstructures, constituent compositions, inclusions, and embedded parts along with geometry information. The independence axiom was used to test the proposed CAD model whether the proposed model satisfied the independence axiom or not. Hence, it was suitable to decompose CAD model of the heterogeneous component into the four sub-models without coupling. The proposed approach was applied for the design of a resistant component.

Yi and Park (2005) developed software in order to analyze and construct the design process of the expanded polystyrene to minimize the cushioning material. The design flow is defined and the software is developed according to the independence axiom of the axiomatic design. A nonlinear finite element analysis program is linked to the developed program for the impact analysis. The developed software is applied to the design of a process of expanded polystyrene cushioning package for a new monitor.

Togay, Dogru, and Tanik (2008) proposed an component-oriented approach based on the axiomatic design theory, namely *Axiomatic Design with Component-Oriented*. In the study, V-Model proposed by Suh and Do (2000) was expanded since the axiomatic design process model did not address component-level architecture issues. Hence it was aimed to develop a new method to combine the Component-Oriented approach with the AD methods. In the proposed study, the information axiom is used to provide guidance on how to construct a Component-Oriented model. The proposed approach was applied to the Federation Development and Execution Process.

3.4. Manufacturing System Design

The Manufacturing System Design is a meta-framework containing tools, methods and processes applicable to the manufacturing design process. A manufacturing system that may change from a manufacturing cell to a large factory consists of machines, materials, people, and information in order to produce a variety of products, services and information (Suh, 2001). The following papers are good examples of design of manufacturing systems based on axiomatic design principles.

Suh, Cochran, and Paulo (1998) developed a method to design an ideal manufacturing system design for manufacturing a mix of large numbers of products of similar-quality over a period of a few weeks based on the independence axiom. Criteria such as quality, cost, and delivery time were taken into consideration for the design. The study was the first study that AD principles for a manufacturing system design were based on the independence axiom. The proposed approach is the first study in which AD principles are used for the design of manufacturing systems and the designers who intend to design a system producing mixed products in accordance with the principles of lean manufacturing production system can use it.

Cochran, Eversheim, Kubin, and Sesterhenn (2000) proposed a method which converted production system to small, flexible, and non-central production units to design a production system that could be managed more effectively. This method was based on the principles of lean management and the independence axiom of axiomatic design principles. The developed method was applied to the production system of a company producing optical tables and vibration isolation systems.

Kulak, Durmusoglu, and Tufekci (2005) proposed an approach to transform traditional production system from process orientation to cellular orientation, based on axiomatic design principles. In their study, a set of functional requirements and design parameters hierarchy for the design of a cellular manufacturing system were presented. The proposed approach was applied to a manufacturing company producing aluminium walkways, bridges, stairs, and ramps (Kulak, 2003).

Houshmand and Jamshidnezhad (2006) proposed an axiomatic design modelling of lean production system design. The proposed model was in the form of functional requirements, design parameters, and process variable relationships providing a scientific model for concepts, principles, and methodologies of lean manufacturing. In the study, many existing implementation shortcomings are eliminated based on the independence axiom with the clarification of interrelationships of concepts, principles, and methodologies.

Nakao, Kobayashi, Hamada, Totsuka, and Yamada (2007) used the independence axiom in order to shorten the lead-time of tailor-made products by eliminating couplings. The decoupling rules, *no feedback from later processes* and *no moving up from later order-received products*, were tested to shorten the lead-time. The first rule shortened the lead time to 2.1 days. The second rule was applied to an unmanned machine shop and it shortened the lead-time from 10.5 to 7.7 days.

Schnetzler, Sennheiser, and Schönsleben (2007) presented a model based on the independence axiom to support supply chain management with information management and information technology. In the study, a methodology was developed to align the activities which were related to information management in supply chains by using the independence axiom. The proposed approach was illustrated by applying it to the business model of Dell Computers and to the supplier and spare parts management of a manufacturer.

Schnetzler et al. (2007) used the independence axiom in order to develop a supply chain strategy. The independence axiom was used to distinguish the objectives and means of supply chain management. The proposed strategy was illustrated by a product family inventory of an electro acoustic company.

Durmusoglu and Kulak (2008) developed a methodology for designing efficient office operations by using the independence axiom. The authors claimed that their methodology would improve office operations and contribute to business competitiveness through a reduction in customer lead time. The developed methodology was effectively used in a loyalty-marketing group of companies for reducing non-value added activities during design process of the cells.

3.5. Decision making

Decision making is defined as an outcome of a cognitive process. In other words, decision making is selecting the most appropriate alternative among several alternatives with respect to the multiple criteria, usually with conflicting or multiple objectives. The following papers present the performance of axiomatic design principles for the solutions of real case decision making problems.

Babic (1999) developed a method which provided an effective decision support system for flexible manufacturing system designers to determine the appropriate flexible manufacturing system configuration at the design stage. The proposed method was based on AD principles and an intelligent system was developed for the design of flexible manufacturing systems. The developed model illustrated the selection of alternatives among machines that produced manufacturing components with respect to the design specifications. The selection procedure was implemented by using information axiom and crisp data.

Kulak (2005) developed a decision support system considering both technical and economic criteria in material handling equipment selection problem. In the developed decision support system called FUMAHES, the final decision for the best equipment selection among the alternatives was given by using the information axiom of the design principles. The Information axiom was integrated with rule-based system in FUMAHES frame which evaluates for the case of both complete and incomplete information.

Kulak and Kahraman (2005a) introduced the information axiom under fuzzy environment. The evaluation of the alternatives and the definition of functional requirements were defined by triangular fuzzy numbers. The proposed approach was applied to multi-attribute comparison of advanced manufacturing systems.

Kulak and Kahraman (2005b) applied the information axiom to a multi-attribute transportation company selection problem. In their study, the problem was taken into consideration by four methods; (1) crisp axiomatic design, (2) fuzzy axiomatic design, (3) analytic hierarchical process, and (4) fuzz analytic hierarchical process.

Kulak, Durmusoglu, and Kahraman (2005) developed weighted and un-weighted multi-attribute axiomatic design approaches including both crisp and fuzzy criteria based on the information axiom. In this study, the weighted information axiom approach for the multi-attribute decision problems was first time proposed in the literature. These proposed approaches were applied to the selection among punching machines while investing in a manufacturing system.

Coelho and Mourão (2007) used axiomatic design principles as a decision making tool to determine one of the manufacturing technologies. The independence axiom was used to check whether the design parameters satisfied the functional requirements or not. Subsequently, the information axiom was employed to select the appropriate technology at a high decision level for the subsequent detail design of a mechanical component.

Kahraman and Cebi (2009) developed the fuzzy information axiom proposed by Kulak and Kahraman (2005a). In their study, three important tolls were added to the fuzzy information axiom method. The first one was the hierarchy toll, which had the ability of taking the hierarchical structures into account. The second was the crisp toll, which had the ability of taking the positive information into consideration under fuzzy environment. The last one was the ranking tool, having the ability of taking the performance of the alternatives. Moreover, the types of decision making problems were classified and the definitions of functional requirements in triangular fuzzy numbers were presented in the study. As a matter of fact, the method was developed to use for the solution of all manners of multi-attribute decision making problems. An application of the developed model was given by a teaching assistant

selection problem to show the usability of the developed method (Cebi, 2010).

Celik, Kahraman, Cebi, and Er (2009) used the fuzzy information axiom to investigate a systematic evaluation model on the docking facilities of shipyards. The information axiom was used for the selection of the best alternatives among shipyards since the information axiom gave the opportunity to decision makers to define the design interval for each criterion.

Celik, Cebi, et al. (2009b) proposed a hybrid approach ensuring the competitiveness requirements for major Turkish container ports based on fuzzy information axiom and fuzzy technique for order performance by similarity to ideal solution methodologies (TOPSIS). The outcomes of the quantitative models were utilized as the data input for SWOT analysis that provided additional contributions for identifying the development strategies on container ports.

Celik, Cebi, et al. (2009a) proposed an integrated model named as *ship of quality* framework in order to make shipping investment decisions. The integrated methodology was based on quality function deployment principles, fuzzy analytic hierarchy process and fuzzy axiomatic design principles. In the study, the independence axiom was used as the inference mechanism for final investment decision. The proposed approach was applied to crude oil tanker markets such as Very Large Crude Oil Carriers, Suezmaxes, and Aframax.

3.6. Theoretical developments and other studies

The studies which propose a new theoretical approach based on axiomatic design principles will be presented in this section.

Donnarumma, Pappalardo, and ve Pellegrino (2002) analyzed the problem by using the soft models of soft dependence of parameters in design systems. A form of computing called Soft Computing, such as Bayesian, the maximum entropy method, and the minimum value of information were used in order to be tolerant to imprecision, uncertainty, and partial truth. The independences of the design parameters were measured by using α and β values of Bayesian. Design parameters were classified into a hierarchic structure according to their effects on the design. The parameters which had the least effect were eliminated from the design. In the study, the independence axiom and information axiom were used for classification and evaluation of independence.

Melvin and Suh (2002) proposed a method for simulating the designs created by using the independence axiom. The simulation based on the independence axiom allowed for the creation of systems with the best probability of satisfying the functional requirements. This proposed approach was applied to machine spindle design.

Su, Chen, and Lin (2003) proposed a new methodology based on the independence axiom. The proposed methodology is based on two algorithms. The first algorithm aimed at measuring the strength of the coupled design tasks. The second algorithm aimed at finding the best processing sequence for the coupled design tasks. The developed methodology transformed the binary structure of the relation matrix into a matrix with quantitative coupling measures. Analytic hierarchy process was used to measure functional dependencies. In the study, a one-time use camera was selected to illustrate the methodology.

Deo and Suh (2004) proposed an approach in order to transform coupled or decoupled design to uncoupled design using the independence axiom. The usage of information transforms at the operational stage was proposed to convert a coupled or decoupled system to an uncoupled system, to achieve robustness in noise factors, and to eliminate imaginary complexity. The proposed approach was applied to automotive suspension systems to illustrate the proposed approach.

Ngai and Jiao (2004) proposed a new approach based on the independence axiom in order to facilitate a factory loading allocation problem. For this purpose, a domain-based approach consisting of five domains, namely, the customer domain, the product family domain, the product volume domain, the final-production location domain, and the sub-production location domain was proposed. The main aim of the proposed approach is to characterize the factory loading allocation problem by representing the dependencies among customers, product families, production volumes, final-production, and sub-assembly supplies.

Suh (2005) used the axiomatic design to reduce or eliminate the complexity of designs via satisfying the FRs of products, processes, operations, and systems within the given constraints. In the study, four types of complexity were defined; (1) time-independent real complexity, (2) time-independent imaginary complexity, (3) time-dependent combinatorial complexity, and (4) time-dependent periodic complexity.

Pappalardo and Naddeo (2005) proposed the value of information approach to find a solution based on the independence axiom of axiomatic design framework when the number of functional requirements was greater than the number of design parameters. The proposed approach was applied to relations between potential failure mechanisms and loading conditions in manufacturing processes.

Suh (2007) presented the usability of AD and complexity theory in Ergonomics. In this study, some examples such as the design of the faucet, and the anthropometric design of the workstation were given to illustrate the usage of AD theories in ergonomic issues. Also, some theorems were proposed which were based on ergonomic principles with respect to the time-independent real and imaginary complexity and time dependent combinatorial and periodic complexities.

Celik (2009a) proposed a hybrid design methodology to combine requirements from the international safety management and ISO 14001:2004 standards into a single execution scheme. For this purpose, analytic hierarchy process and fuzzy information axiom were used to structure an integrated model for ship management companies.

Celik (2009b) proposed a model in order to redesign the traditional management style of global shipping firms for the purpose of establishing an Integrated Process Management System. The requirements of ISO 9001:2000, ISO 14001:2004, and OHSAS 18001:2007 were evaluated with respect to International Safety Management Code clauses. The information axiom of fuzzy axiomatic design principles and analytic network process were used to identify critical managerial processes of shipping business.

Celik (2009c) proposed a systematic approach in order to structure an integrated quality and safety management system for shipping operations by exploring the compliance level of the international safety management code with the ISO 9001:2000 based on fuzzy information axiom. An oil tanker ship having a casualty onboard was analyzed to illustrate the use of the proposed approach.

4. Conclusion, research applications and limitations

In the recent years AD principles, which provide decision makers with solutions in many areas particularly design problems, have been used widely in different practice areas. A comprehensive survey which evaluates and classifies both theoretic and practical articles and defines future trends has been investigated with this study for the first time in literature.

Upon the evaluation of the studies, it is ascertained that AD principles are widely used for the provision of solutions to particularly design problems. The percentage of the prepared papers

aimed at designing is 74.6% (47 articles), the rest includes other areas such as supply chains and multi-criteria decision making. In the articles, solving design problems and areas of product and software design come forth with 42.5% (20 papers) and 23.4% (11 papers), respectively.

System design and production systems for design application areas have lower percentages in comparison with 19.1% (nine papers) and 14.9% (seven papers), respectively. In connection with the shortening the product life and software life cycle periods due to customer requirements of today, the number of practices is increasing from day to day. Nonetheless, although AD principles are used in the design of complicated systems such as the design of production systems they are not at the expected level due to the distinctive difficulties of system design. Independence axioms (axiom 1) are used as the main axiom in practices aimed at design problems. 71.4% (45 articles) of the research studies which were carried out have used the independence axiom. The independence axiom is used widely as it makes individuals more creative, as they reduce random research processes and also as they form a scientific infrastructure for the world of design by minimizing the repeated trial-and-error activities.

When the studies presented, especially in the last few years, are evaluated it is determined that there is an increase in the trend of practical and theoretical studies aimed at multi-criteria decision making problems. The studies in this application area have a percentage of 22.2% (14 papers) and information axioms are generally applied in these studies. Information axioms give decision makers an important advantage over resolving multi-criteria decision making problems as they allow for the evaluation of the complete and incomplete information criteria together. Also, the fact that they allow for the selection of not only the best alternative within the criteria of the decision makers but also the most appropriate alternative is another important advantage. In the conclusion of the evaluation as it was suggested by Suh (1991); there is not a study present which allows for the selection of the best design, which was developed by taking independence axioms as its basis, with information axioms. In the future studies directed at this can be prepared.

In conclusion of the evaluation 39.6% (25 articles) of the studies are directed only at the application of AD principles. On the other hand, 23.8% (15 articles) of the studies are those which allow for theoretical development to AD principles. The remaining studies are those where AD principles are integrated by different methods (TOPSIS, Expert system, etc.).

Although this study is a comprehensive study where the previous studies taking AD principles as their basis are examined, there exist certain limitations. Studies between the years of 1990 and 2009 have been researched by only using key words such as “Axiomatic design”, “Independence Axiom”, and “Information Axiom”. As a result, it does not contain present papers which are remaining outside of the limitations of the key words stated above. In addition, databases such as Scencedirect, Taylor & Francis, and Web of Science have been used during the research. Studies published in academic journals outside of these databases have not been included. Lastly, non-English papers have not also been included in this research.

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