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Application of Axiomatic Design in manufacturing system design: a literature review

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Abstract

Axiomatic Design (AD) is applied not only in product development, but also in many other applications. Through the systematic approach and the consideration of Independence Axiom and information Axiom, even highly complex projects can be mastered reducing the complexity in the design task. In addition to product design, system design, software design and many other fields, Axiomatic Design is also used in the design of manufacturing systems. In form of a literature review, this paper studies the beginnings of AD in Manufacturing System Design and its development in the field of production. The data basis of this analysis are the works indexed in the Scopus about Manufacturing Systems with the keyword Axiomatic Design. In a first step, the paper examines, when the application of AD in Manufacturing System Design has begun and investigates the number and type of publications dealing with this methodology in Manufacturing. In a second step, the paper explores for which specific topics AD has been applied over the years, and which are current and future tasks for AD in Manufacturing System Design.

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Keywords: Axiomatic Design; Manufacturing Systems; Design Theory; Literature Review

1. Introduction

Axiomatic Design has established itself as a method for the system design and is mainly used in the design of highly complex systems. In addition to many other complex issues and decision problems, Axiomatic Design is also used more and more for the design of Manufacturing Systems. Due to its systematical character and the top-down approach, it is suitable to structure complex problems into smaller and manageable work packages. Through the application of the axioms (Independence and Information Axiom) solutions and Design Parameters can be defined independent of each other determining also the best solution alternative for a system.

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 [1]. This paper is focused primarily on the area of Manufacturing System Design investigating the development and the application of AD by an analysis of the literature of the past 20 years. The literature review attempts to answer different questions. The first question, which should be answered, is whether AD has a rising or falling trend in Manufacturing Systems Design. First suspicions lead to an increasing number of users, which has to be confirmed by the analysis. Another issue arises with respect to the focus of the application of AD. The analysis should also indicate which axioms are predominantly used and whether all four domains are usually used and examined or not. It also applies to define, whether AD is only used for applications, or whether there are also theoretical works on its further development in the field of Manufacturing Systems Design. Finally, it is also of interest whether AD in Manufacturing System Design is used worldwide or just in certain parts of the world. Finally, it should also be investigated, which topics were in the focus in recent years and whether certain trends and tendencies for the future can be identified.

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2. Principles and basics of Axiomatic Design methodology

This section will briefly introduce the methodology of AD presenting the basics of the AD approach and actual fields of application.

2.1. Introduction in Axiomatic Design

The theory of Axiomatic Design is applicable to many different fields and kind of systems. Nam P. Suh developed this approach in the mid-1970s in the pursuit of developing a scientific, generalized, codified, and systematic procedure for design. In order to systematize the thought process and to create demarcation lines between various design activities, four domains represent the foundation of Axiomatic Design procedure: 1) the Customer Domain, 2) the Functional Domain, 3) the Physical Domain and 4) the Process Domain [2]. The Customer Domain contains the so called customer-benefit attributes (CAs; Customer Attributes), the Function Domain is derived from this and contains the functional demands (FRs; Functional Requirements), the Design Domain provides Design Parameters (DPs) for the consequent implementation of the FRs, transformation into processes thereof shall be regulated by the Process Variables (PVs) in the Process Domain [3]. The core of the Theory of AD is represented by two axioms, the Independence Axiom (1st axiom) and the Information Axiom (2nd axiom), as necessary and sufficient condition for a “good” design of a product or a system. For this purpose, FRs and DPs are mathematically represented as vectors {FR} and {DP}.

The Design Matrix describes the relation between these two vectors:

$$\{FR\} = [DM]\,\{DP\} \tag{1}$$

where $$DM_{ij} = \frac{\partial FR_i}{\partial DP_j} \tag{2}$$

The Independence Axiom (Axiom 1) recommends the independence of each functional requirement. The Independence Axiom states that when there are two or more FRs, the design solution must be such, that each one of the FRs can be satisfied without affecting the other FRs [3]. A good design is potentially achievable if exactly one Design Parameter (DP) can be identified to fulfill the allocated FR without affecting the other FRs. To fulfill the Independence Axiom, the Design Matrix must be either a diagonal or a triangle matrix. In case of the diagonal matrix, it is called an “uncoupled” design. This is the ideal case, as every FR can be fulfilled with exactly one DP without any interrelation to other FRs. The triangle matrices represent a so called “decoupled” design. These functions can only be satisfied independently from each other by respecting a certain sequence. All other cases represent a (badly) “coupled” design [3].

The Information Axiom (Axiom 2) inspires the minimization of the information content of the design. The Information Axiom is defined in terms of the probability of successfully achieving FRs or DPs and states that the design with the least amount of information is the best to achieve the functional requirements of the design.

Usually the AD design tasks start with the decomposition of the problem. The development of FRs and DPs hierarchy is achieved by “zigzagging” between the two domains, respectively Function Domain and Design Domain. After defining the FR of the top level, a first level design concept (DP) has to be generated. In the next steps of decomposition also for lower levels FR-DP combination have to be developed achieving more and more “concrete” design solutions. During this mapping process between the domains the two fundamental axioms have to be respected and considered as basis for evaluating and selecting designs alternatives in order to generate a robust design [3].

2.2. Application of Axiomatic Design in Manufacturing Systems Design

The origin of Axiomatic Design methodology lies in Product Development. Usually products need to be designed to fulfill the customer needs to guarantee functionality and also success on the market. Thus, Axiomatic Design was used at its beginnings mainly for Product Development and Systems Design. The theory of Axiomatic Design is applicable to many different kinds of complex systems [3]. Actually, Axiomatic Design is used in many different areas such as Software Design but also for the design of large and complex systems.

Kulak et al. [1] identified in his literature review about the application of Axiomatic Design the following application areas ranked by number of papers:

- Product Design
- Decision Making
- Software Design
- System Design
- Manufacturing System Design
- Others.

A Manufacturing system can be defined as a large and complex system, be-cause it is subject to temporal variation and must be reconfigurable and adaptable. In such cases Axiomatic Design shows a suitable and helpful method to re-duce complexity in the manufacturing systems design [4].

Axiomatic Design provides a systematic approach to derive in a first step, the functional requirements (FR) and in a second step a set of design parameters (DP) for Manufacturing Systems. By applying the Axiomatic Design methodology [5] and the MSDD approach of Cochran et al. [6] the requirements and specific design parameters could be achieved in a systematic and structured way. Cochran's methodology "Manufacturing System Design Decomposition" (MSDD) is often used in Manufacturing Systems Design to illustrate the derivation of the FR-DP tree in a very easy and clear form. The graphical illustration helps to identify the ideal sequence to implement the Design Parameters at the lowest level.

3. Literature review methodology and results

In the following part of the Literature Review is presented. first the research methodology. After this, the results of the analysis are shown and commented.

3.1. Approach to conduct the literature review

As a basis for the Literature Review the papers from the database Elsevier's Scopus were analyzed using the following selection criteria:

- Period of the last 20 years (1996-2015)
- Keyword "axiomatic design" and "Manufacturing System"
- Origin language English.

Using the above mentioned search criteria 61 papers could be identified. From this 61 works 52 papers remained for a deeper literature analysis. The remaining nine works were excluded from the analysis for the following reasons:

- they deal with Product Development and not with Manufacturing Systems Design
- they report from other sectors (service industry and hospitality)
- they mention AD only in few words as possible methodology for systems engineering.

The remaining 52 works were subjected to a detailed analysis in order to give an answer to the questions described in the introductory part. The complete data set is shown in table 1 at the end of the paper.

3.2. Frequency-years analysis

Figure 1 shows the number of papers over the period from 1996 to 2015. It is shown first a clear upward trend of papers shows which use AD as a method for the design of Manufacturing Systems. A special accumulation of works can be identified in the years 1999-2001 (mainly Lean and Flexible Manufacturing Systems), from 2005-2007 (mainly characterized by works about Reconfigurable Manufacturing Systems) and from 2012 onwards (Agile and Changeable Manufacuring Systems and modern topics like Sustainability, Life Cycle Management or Cloud Manufacturing).

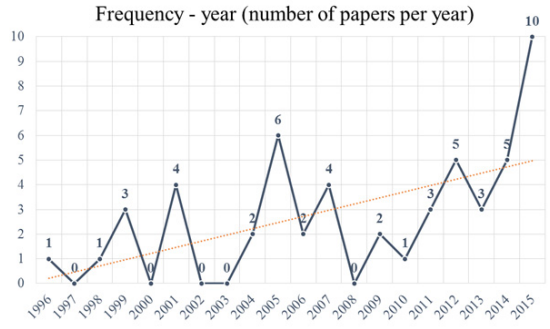

Fig. 1. Frequency – year graphic.

3.3. Consideration of Axioms in the analyzed papers

Figure 2 shows how many of the works focus in specific the axioms of AD. While most studies point out the Independence and Information Axiom in their literature analysis, only few apply both axioms in their research. The figure clearly shows that predominantly (70%) the Independence Axiom is applied and deeper analyzed. Only about 10% deepen their work also with the help of the Information Axiom or both of them. Approximately another 10% of the research papers involves any of the axioms in a more detailed investigation.

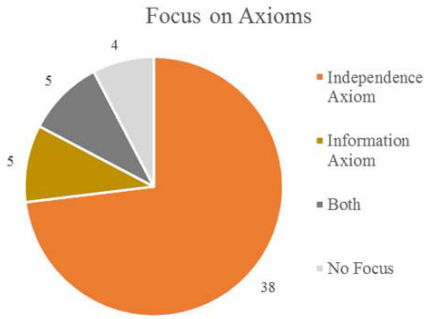

Fig. 2. Focus on Independence or Information Axiom.

3.4. Domains treated (CA, FR, DP, PV)

Figure 3 shows the application of the domain levels in the various papers. The picture clearly shows that mainly an association of FRs and DPs takes place by the execution of the decomposition and mapping process. Very few works already start with the analysis of Customer Attributes (CAs), which provide an important basis for the derivation of later FRs. In addition, only a few studies were identified, that deal after their FR-DP decomposition with the derivation of concrete Process Variables (PVs). CAs quite strongly influence the results of the AD applications and the derivation of PVs is necessary to achieve practically applicable solutions. These results leaves open question whether additional research instruments or methods for the integration of CAs and the derivation of PVs are needed in the future or not.

Fig. 3. Domains treated in the works.

3.5. Theoretical work versus applications of AD

Fig. 4 shows a comparison between theoretical works on the development of the AD approach for Manufacturing Systems Design and on the other hand practically oriented research papers with applications of AD for the design of Manufacturing Systems. Over 75% of the analyzed research works use AD as existing methodology for the design of different complex systems in manufacturing.

The method therefore is very popular in the practical application. This could be interpreted also as an indicator for their suitability in Manufacturing Systems Design. However, it is also very positive that many scientists are working to develop and to optimize the AD-method. This ensures in the future, that the method is continuously adapted and developed to meet new future challenges.

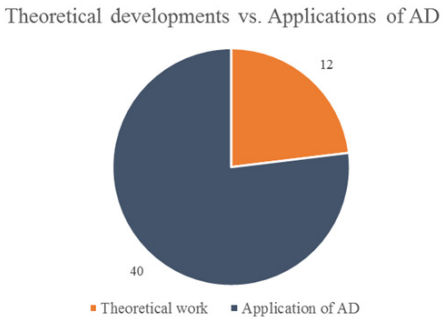

Fig. 4. Theoretical works versus AD applications.

3.6. Document types

Figure 5 shows the type of publication of the 52 analyzed works. The results show that 60% of the works have been published in renowned academic journals. 37% of the papers have been presented and discussed on international conferences (mainly ICAD community). Only a small amount of works has been published as a book or book chapter. The most important Journals treating AD for Manufacturing System Design in Scopus are the International Journal of Production Research (6 articles) and CIRP Annals Manufacturing Technology (4 articles).

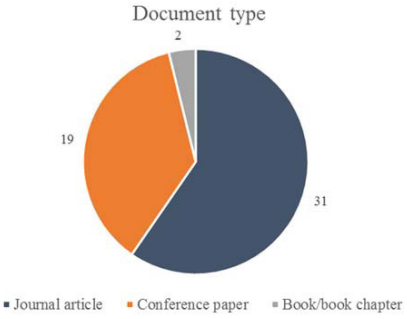

Fig. 5. Types of documents.

3.7. Origin of papers (countries)

Figure 6 shows the origin of the authors by country. According the results, most of the articles and papers have been written by scientists from the United States, Turkey and Italy. Other nations that deal also with AD in the area of Manufacturing System Design are Canada, India, Iran, China, Sweden, United Kingdom, Germany and Hong Kong.

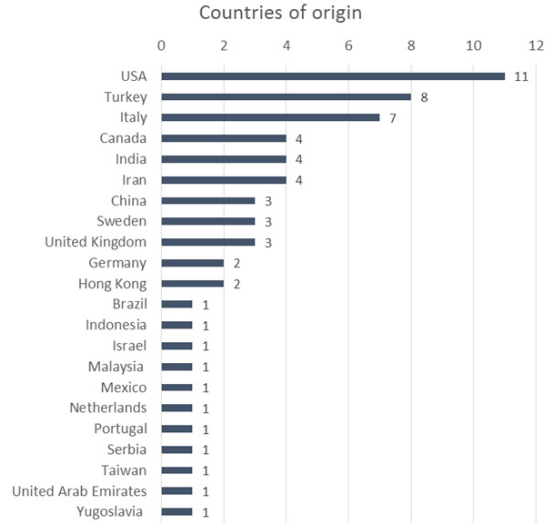

Fig. 6. Authors countries of origin.

3.8. Specific topics dealing with AD in Manufacturing Design and their development over the years

Figure 7 shows the main specific topics of the research papers. It can be seen that AD was applied over all the years as a tool for general aspects in Manufacturing System Design. From 2000 AD has been widely applied for lean, flexible and reconfigurable systems. Later was added the aspect of agility and changeability. In recent years, AD was also used for automation, material handling and lifecycle management. Recent topics include Cloud Manufacturing, Sustainability and Distributed Manufacturing.

	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
Manufacturing Systems and Processes in General	1			1	1		2			1	3									3
Lean Manufacturing Systems					1						1			2			1			
Flexible Manufacturing Systems					1												1			
Cellular and reconfigurable Manufacturing Systems									1	1		1						1	1	2
Agile/changeable Manufacturing Systems						1						1				1	1			2
Virtual and Computer Integrated Manufacturing						1				1					1			1	1	
Hybrid and Automated Manufacturing Systems												1				1	1		1	
Material Handling and Transport in Manufacturing										1	1					1	1			
Lifecycle Management												1								2
Distributed Manufacturing																		1		1
Sustainable Manufacturing																			1	
Cloud Manufacturing																			1	

Fig. 7. Specific topics of interest for AD in Manufacturing Systems Design.

Table 1. Classification of literature review 1996-2015 (20 years)

		Axiom		*Domain Level*				*Type*		*Main specific topic*													
	Author	Independence	Information	Customer Attribute (CA)	Functional Requirement (FR)	Design Parameter (DP)	Process Variable (PV)	Theoretical work	Application of AD	Manufacturing Systems and Processes in general	Lean Manufacturing Systems	Flexible Manufacturing Systems	Cellular and reconfigurable Manufacturing Systems	Lifecycle Management	Hybrid and Automated Manufacturing Systems	Holonic/agile/changeable Manufacturing Systems	Virtual and Computer Integrated Manufacturing	Sustainable Manufacturing	Cloud Manufacturing	Material Handling and Transport in Manufacturing	Distributed Manufacturing
[7]	Farid and Ribeiro (2015)	✓						✓					✓								
[8]	Puik et al. (2015)	✓			✓	✓	✓	✓					✓								
[9]	Gabriel-Santos et al. (2015)	✓			✓	✓			✓	✓											
[10]	Rauch et al. (2015)	✓		✓	✓	✓			✓												✓
[11]	Holzner et al. (2015)	✓		✓	✓	✓			✓							✓					
[12]	Weber et al. (2015)	✓			✓	✓			✓							✓					
[13]	Michaelis et al. (2015)				✓	✓		✓		✓											
[14]	Barker and Summers (2015)	✓		✓	✓	✓			✓					✓							
[15]	Barker and Summers (2015)	✓			✓	✓			✓					✓							
[16]	Mollajan and Houshmand (2015)	✓	✓		✓	✓	✓	✓		✓											
[17]	Farid (2014)							✓					✓								
[18]	Valilai and Houshmand (2014)	✓			✓	✓	✓		✓										✓		
[19]	Taha et al. (2014)	✓			✓	✓			✓								✓				
[20]	Bahadir and Satoglu (2014)		✓		✓	✓			✓						✓						
[21]	Taisch et al. (2014)	✓			✓	✓			✓									✓			
[22]	Farid (2013)							✓					✓								
[23]	Matt and Rauch (2013)	✓		✓	✓	✓			✓												✓
[24]	Han et al. (2013)	✓			✓	✓	✓		✓								✓				
[25]	Molina and Sanchez (2012)	✓		✓	✓	✓			✓			✓									
[26]	Vinodh and Aravindraj (2012)	✓			✓	✓	✓		✓		✓										
[27]	Ertay and Satoğlu (2012)		✓		✓	✓			✓						✓						
[28]	Matt (2012)	✓	✓		✓	✓		✓								✓					
[29]	Petrović et al. (2012)							✓												✓	
[30]	Durmusoglu and Satoglu (2011)	✓			✓	✓			✓						✓						
[31]	Vinodh (2011)	✓			✓	✓	✓		✓							✓					
[32]	Matt et al. (2011)	✓			✓	✓			✓											✓	
[33]	Mokhtar and Houshmand (2010)	✓			✓	✓			✓								✓				
[34]	Jadeja et al. (2009)	✓			✓	✓			✓		✓										
[35]	Jadeja et al. (2009)	✓			✓	✓			✓		✓										
[36]	Stiassnie and Shpitalni (2007)	✓	✓		✓	✓			✓					✓							
[37]	Satoğlu and Durmuşoğlu (2007)	✓			✓	✓			✓						✓						
[38]	Matt (2007)	✓			✓	✓			✓							✓					
[39]	Bi et al. (2007)	✓			✓	✓			✓				✓								
[40]	Jang (2006)	✓			✓	✓			✓											✓	
[41]	Houshmand and Jamshidnezhad (2006)	✓			✓	✓	✓		✓		✓										
[42]	Kulak et al. (2005)		✓					✓		✓											
[43]	Suh (2005)	✓	✓		✓	✓		✓		✓											
[44]	Kulak (2005)		✓		✓			✓												✓	
[45]	Kulak et al. (2005)	✓			✓	✓			✓				✓								
[46]	Almström (2005)	✓			✓	✓			✓	✓											
[47]	Kulak and Kahraman (2005)		✓		✓			✓									✓				
[48]	Liu et al. (2004)	✓			✓	✓			✓	✓											
[49]	Luo et al. (2004)	✓			✓	✓			✓				✓								
[50]	Li et al. (2001)	✓			✓	✓			✓	✓											
[51]	Gu et al. (2001)	✓			✓	✓	✓		✓	✓											
[52]	Chen et al. (2001)	✓			✓	✓			✓								✓				
[53]	Nucci Franco and Batocchio (2001)	✓			✓	✓			✓							✓					
[54]	Charles et al. (1999)	✓		✓	✓	✓			✓	✓											
[55]	Babic (1999)	✓	✓		✓	✓			✓			✓									
[56]	Duda et al. (1999)	✓			✓	✓			✓		✓	✓									
[57]	Suh et al. (1998)	✓			✓	✓			✓	✓											
[59]	Park et al. (1996)	✓			✓	✓	✓		✓	✓											

4. Conclusion and outlook

The Literature Review has shown that AD becomes more and more important for Manufacturing Systems Design. The increasing number of research papers in the last years confirms a growing community of scientists dealing with AD in Manufacturing. In most of the research works the Independence Axiom is mainly applied and highly discussed by decomposition of FRs and DPs. The results of the literature review lead to a conclusion, that there are not so many research works dealing and investigating the Information Axiom in Manufacturing Systems Design. This could encourage scientists to discuss in the future also the quality of solution alternatives by the use of the Information Axiom. At the domain level, the decomposition between FR and DP are treated in most of the works. The CAs and PVs play only a subordinate role. Due to the fact, that CAs are highly important to define the right first level FRs and DPs the should be considered more in future works. Future works should also not stop at the domain level of DPs deriving also PVs for a later practical implementation of the elaborated design. As shown in the literature review, AD is mainly used as a method for practical applications and case studies of Manufacturing System Design. Only few works are dealing also with a further development and adaption of AD-methodology to the design of manufacturing systems. The analysis of previous and actual specific topics of AD application is showing, that it is increasingly used also for new challenges in Manufacturing like Sustainability in Manufacturing, Cloud Manufacturing or Agile/Changeable Manufacturing Systems.

Summarizing, AD is becoming an important instrument and design methodology in the Manufacturing Systems community. More and more scientists over the world are using the methodology for the design of manufacturing systems and related system design problematics.

In a next step the shown literature review will be extended through an analysis of research works dealing with Axiomatic Design for Manufacturing Systems Design in further scientific databases for literature like Thomson Reuter's Web of Science (WoS) and published in a Journal article.

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