

# Applications of Axiomatic Design Theory in Design for Human Safety in Manufacturing Systems: A Literature Review

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**Abstract.** Design for Human Safety (DfHS) is an approach to integrate knowledge of human safety in the design process. DfHS is multi-disciplinary in its nature, requiring many kinds of information and knowledge. Number of DfHS studies tried to apply Axiomatic Design (AD) to achieve their aims. The purpose of this paper is to review the literature on application of AD in DfHS in manufacturing systems and to propose a roadmap for future DfHS works. This paper examines the number and type of publications dealing with this context. The review covers papers published between 1990 (when AD was introduced first) and 2017. It is based on a range of combinations of the following keywords: “Axiomatic design” and “safety” or “accident” or “hazard” or risk”. This review has identified 15 research topics that were clustered into three main research groups: (1) application of AD in ergonomic design; (2) application of AD in human-computer interaction; and (3) application of AD in integrating safety systematically in design process. The authors also tried to identify which axiom of AD has been used in these researches.

Keywords: Design for human safety; Axiomatic design; literature review

## 1 Introduction

During recent decades, there has been a growing awareness of human safety in the design process. The main responsibility of making a machine safe lies in the design process [1]. In this context, the term “Design for Human Safety” (DfHS) captures this effort to integrate the knowledge on human safety in the design process [2].

A large number of studies, applied design theories, methodologies, tools and/or techniques for considering safety in the design process. Nowadays, Pahl and Beitz’s Systematic Approach (SA) [3] and Suh’s Axiomatic Design (AD) theory [4, 5] are some of the most widely accepted design theories. Pahl and Beitz describe a product development process as a series of transformations, from problem description to requirements list, to principal solutions and working structures, to preliminary design, to detailed layouts, and to final layout, form/dimensions, and manufacturing specifications. The design activities are classified into: product planning, conceptual design, embodiment design, and detail design. Suh’s AD provides the fundamental axioms for analysis and decision making.

AD theory appears to be more effective in the context of DfHS. This theory is useful in this context because of its capacity to present design requirements and associated design parameters, and including criteria for evaluating designs. In recent years, there have been attempts to apply AD principles in DfHS. 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. The integration of AD with other design theories, methodologies, tools and/or techniques, such as the systematic approach, has been also appeared in the literature.

This paper focuses primarily on the area of DfHS and investigates the development and the application of AD by an analysis of the literature during the past years. The literature review attempts to answer different questions. The first question to be answered is whether AD has a rising trend in DfHS or a falling one. More precisely, in this paper, we address the following question: How AD can be used to improve human safety early in design process. It should also be investigated, which topics were focused in recent years and whether certain trends and tendencies for the future can be identified in DfHS context. The analysis should also indicate which axioms of AD are predominantly used.

The remainder of this paper is arranged as follows: Section 2 introduces the AD theory, its four fundamental concepts and actual fields of application. In Section 3, our literature review methodology review is described. Section 4 reviews the literature for available researches based on application of AD in DfHS. Section 5 provides a discussion on the chronological and thematic perspectives. This section also identifies the future works regarding AD application in DfHS. Finally, the conclusions are given in Section 6.

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## 2 Axiomatic design and its application fields

This section will briefly introduce the AD theory, its four fundamental concepts and actual application fields.

### 2.1 Introduction to AD

The AD theory was introduced by Suh in 1990. Its goal is to “establish a scientific basis to improve design activities by providing the designer with a theoretical foundation based on logical and rational thought processes and tools” [4]. It insures an efficient approach fulfilling “what we need” by “How we are going to satisfy the requirements”. This theory consists of four fundamental concepts [4, 5]:

#### 2.1.1 Design as a mapping process

According to AD, design is made up of four domains. The customer domain is characterized by the needs that the customer is looking to satisfy in a product, process, system or materials. In the functional domain, the customer’s needs are specified in terms of Functional Requirements (FRs) and Constraints (Cs). In order to satisfy the specified FRs, Design Parameters (DPs), which are the key variables, are conceived in the physical domain. Finally, to produce the product specified in terms of DPs, AD develops a procedure characterized by Process Variables (PVs) in the process domain (Figure 1).

#### 2.1.2 Top-down hierarchical design structure

Design usually consists in decomposition with multiple abstraction levels (Figure 1). The higher levels are more abstract; where the lower ones are more detailed. The design process has to begin at the system level and continue through more detailed levels until reaching a point of sufficient clarity to represent the design object. This process is called hierarchical decomposition and its outcome is depicted by a tree-model in each of the four domains.

#### 2.1.3 Design matrix

The relationship between FRs and DPs is represented in a matrix which allows evaluating the structure of the product. This matrix is called the ‘design matrix’ which links FRs to DPs and characterizes the product design. When the design matrix is diagonal, the design is called an “Uncoupled design”. The design is called a “Decoupled design” when the design matrix is triangular. A coupled design occurs when the design matrix is a full one. Both uncoupled and decoupled designs satisfy the independence axiom and are considered acceptable in axiomatic design.

#### 2.1.4 Design axioms

Suh [4] formulated two axioms for good design:

- (1) The independence axiom: maintains the independency of the FRs. In an acceptable design, mapping between the FRs and the DPs is such that each FR can be satisfied without affecting the other FRs;
- (2) The information axiom: minimizes the information content of the design. If a set of designs satisfy the same FRs and conforms to the independence axiom, the best is that with the minimum information content. The information axiom provides a quantitative measure of the merits of a given design.

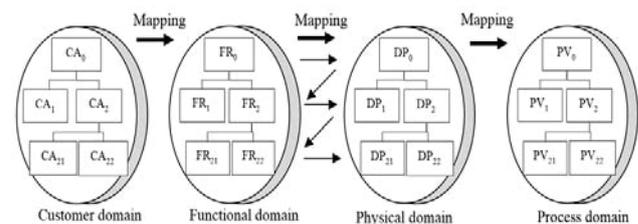


Fig. 1. Axiomatic design approach.

The reader is referred to [4, 5] for further details on AD, its concepts and architecture.

### 2.2 AD and DfX

AD theory is used in many different areas such as software design but also for the design of large and complex systems. Kulak et al. [6] identified the application of AD for the following areas: decision making, software design, system design, manufacturing system design, and others.

Design for X (DfX) is one of the most effective approaches to make the product better suited for its life phases, and increase the general virtues of the product in order to improve its performance [7]. According to [8, 9], X represents a specific property (e.g., quality, safety); and a life-cycle phase of the product (e.g. manufacturing and assembly).

In the past 20 years, there have been attempts to apply AD principles in DfX. Such as Application of AD in: Design for manufacturing, e.g., [10–12]; Design for cost, e.g., [13]; Design for quality, e.g., [14]; Design for recycling, e.g., [15]; Design for human safety e.g., [2]; and etc.

The purpose of this paper is to review the literature on application of AD in design for human safety (DfHS) in manufacturing systems.

## 3 Literature review methodology

The aim of this step is to collect enough appropriate publications related to application of AD in DfHS research. This section provides an overview and analysis of studies carried out based on (1) the author(s) name(s), (2) title of the paper, (3) the year of publication of each paper and (4) the title of the journal. This search strategy was developed by first identifying the relevant time frame, data sources and key words. Initially, this study

focused on literature published between 1990 (when AD was introduced) to 2017. The preliminary search was conducted on five databases including Elsevier, Springer, Taylor & Francis, Wiley Online Library, and American Society of Mechanical Engineers (ASME). The five databases involved the main peer-referred journals on the topic of DfHS.

In the preliminary search, a search was made under the “Title” criteria in the databases, with the full search schema “Title ((Axiomatic design) and (safety))”. Whereas, from preliminary search, many of papers could be found, we tried to eliminate some of them. In order to ensure the papers selected were of high quality, six journals focusing on application of AD in DfHS were chosen. Three of these journals are leading journals in the field of “engineering design”. Two of them are in the field of “safety management”. The remaining two are also leading journals in the field of “ergonomics”. The secondary search within these six selected journals was made using the “Title/Abstract/Keyword” criteria. As none of the databases covered all the aforementioned journals, different databases had to be used. The search strategy initially identified keywords that could be associated with application of AD in DfHS. The search was based on a range of combinations of the following keywords: “Axiomatic Design” and “safety” or “accident” or “hazard” or risk”. Finally, we did not limit the potential journals to cover a diverse range of publication formats including conference proceedings (specially International Conference on Axiomatic Design (ICAD) proceedings), theses and books. To ensure completeness, an Internet search was also conducted using a similar process to that used with the library databases. The search was conducted using the same keywords in the secondary search. The results of these searches were combined to provide a total of 22 documents.

### 3.1 Literature selection

The objective of this review was not to obtain a complete list of papers, but rather to explore the current trends, useful findings and research gaps of application of AD in DfHS. On the other hand, some of the selected papers that did not match the subject but matched the research schema were selected. It was essential to make further efforts to screen and filter the 22 papers for in-depth review. In the relevant papers selection, two filter criteria were used to further select relevant papers for in-depth review and analysis: (1) the papers were focused on application of AD in improving safety in domains other than design and manufacturing systems, for instance, construction safety; and (2) only the words in the search terms were mentioned, but not studied in depth. After applying the selection criteria, 15 relevant documents remained. Figure 2 shows relevant papers in the six journals, ICAD proceedings and other publication formats. This figure clearly shows that predominantly (40%) relevant papers are in ICAD proceedings.

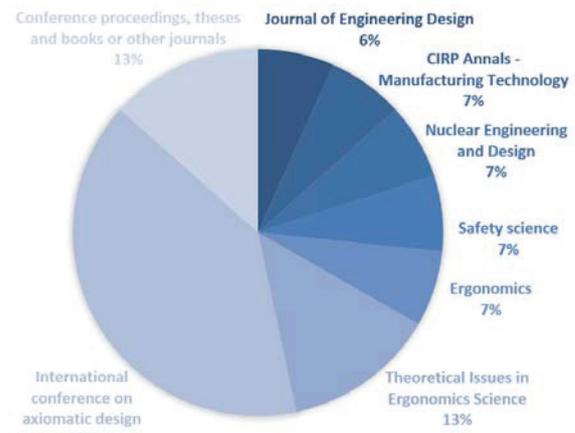


Fig. 2. The number of papers related to application of AD in DfHS.

## 4 Results and analysis

Initially, the search terms identified some 22 journal articles, conference proceedings, theses and books, handbooks or reports. These were then carefully filtered to establish 15 documents that were clustered into three main following research groups: (1) application of AD in ergonomic design; (2) application of AD in human-computer interaction; and (3) application of AD on integrating safety systematically in design process. In the following section, a brief description of each group is described.

### 4.1 AD and ergonomic design

An axiomatic approach to ergonomic design and a universal measure of system-human incompatibility was introduced by Karwowski [16]. Karwowski describes the rules of good ergonomic design which consists of human-design compatibility (Figure 3). The two axioms of axiomatic design were adapted for ergonomic design purposes. Axiom 1 stipulates the independence of the functional compatibility requirements and Axiom 2 stipulates the need to minimize the incompatibility content of the design. Ergonomic design is defined as mapping from system-human compatibility needs to relevant compatibility requirements. System-human compatibility is expressed in terms of human abilities and limitations at the beginning of the design process. Hazard prevention aspects are not taken into account.

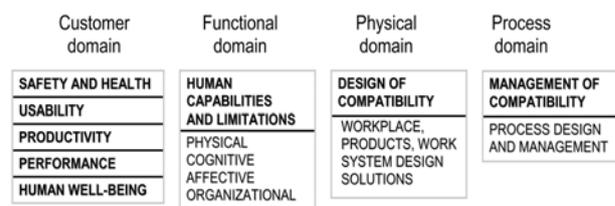


Fig. 3. Four domains of design in ergonomics [16].

Heo and Lee [17] proposed a methodology to examine the design process using AD as a measure for evaluating safety. This is particularly important for

identifying vulnerabilities and creating solutions. To improve performance and safety, various design strategies such as independency and redundancy were implemented. The authors suggested an alternative viewpoint for evaluating deployment of design strategies in terms of AD. AD suggests two design principles and visualization tools for organizing the design process. The major benefit of AD is that it is capable of providing suitable priorities for deploying design strategies. AD principles were used to develop a fault tree to analyse the reliability of the design parameters used to meet the functional requirements.

#### 4.2 AD and human-computer interaction

Helander and his colleagues illustrated the applicability of AD principles in human factors design and human-computer interaction (HCI).

Helander and Lin [18] demonstrated the use of AD for the anthropometric design of workplaces. They showed how the formulation of FRs and DPs can help in conceptualizing design principles and selecting design parameters for a seated work place. Their research suggested a new way of calculating the information contents in anthropometric design by redefining the concepts of system range and design range. The two axioms fit well with the type of design methodology that has been developed in ergonomics over the years. (1) It has been well recognized that formulations of functional requirements are essential to ergonomics design. (2) In ergonomics design, minimization of information has long been recognized as an important criteria.

Helander and Lin [19] demonstrated how AD can be used for biomechanics design of hand tools and for anthropometric design of workplaces. For this aim, they used two axioms of AD theory. The first axiom was used to demonstrate how design activity can be structured to avoid time-consuming iterative improvements of design solutions. The second axiom was used for anthropometric design of a work place.

Helander and Jiao [20] suggested that the AD framework could be used to analyse and reduce coupling in software usability heuristics. To uncouple the design a cluster analysis was performed on the original design matrix. Then, FRs were split and recombined in order to reduce the coupling.

Helander [21] and Lo & Helander [22] extended previous efforts and developed a Design Equations for Systems Analysis (DESA) methodology (Figure 4) based on the principles of AD. The aim is to identify and suggest avenues for eliminating coupling between user goals and user actions. This methodology consists of four domains, namely user goals, functional requirements, design parameters and user actions, to model the human-machine system functionally and structurally. However, this methodology describes the rules for achieving a usable design and then takes into account only the user actions to meet a specific goal. Thus, in performing a global analysis it consists of solutions from the standpoints of design and usability.

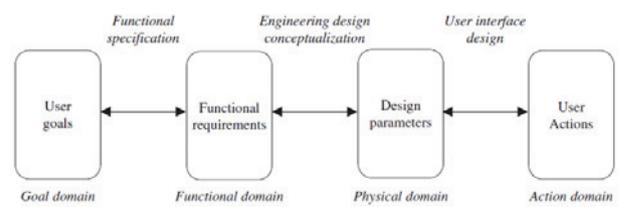


Fig. 4. DESA framework [22].

#### 4.3 AD and integrating safety systematically in design process

To integrate safety systematically from the early design process, [23–26] first sought to formulate a systematic description of the design process. To this end, they used the “extended axiomatic design” (EAD) proposed by [27]. EAD combines the systematic approach [3] and axiomatic design [4, 5]. It consists of considering that three of the four phases of the systematic approach, i.e. conceptual, embodiment and detailed design, are divided into two domains: functional and physical (Figure 5).

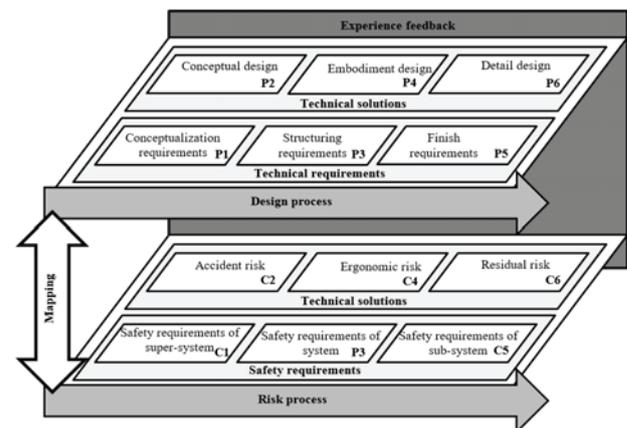


Fig. 5. IRAD framework [23].

Ghemraoui et al. used the systematic approach to formulate a typology of safety objects at each design phase [23–25]. To satisfy safety needs, they adopted a representation for the design process that links the systematic approach to AD [4, 5]. The method proposed, Innovative Risk Assessment Design (IRAD), consists of a general suggestion for systematic risk identification and human-safety integration in the early design phase. It considers design as an iterative activity between a design process and a risk process. These two processes evolve simultaneously and influence each other. The design process is divided into six phases. Similarly, the risk process is divided into six contexts. This method consists of a general suggestion for systematic risk identification and human-safety integration in the early design phase. Consequently, IRAD considers design as an iterative activity between a design process and a risk process (Figure 5). Other paper of Ghemraoui et al. [26] deals with the problem of defining safety objectives early in the product design process. They show that there are different typologies of safety objectives depending on the evolution of the product.

Sadeghi et al. attempted to operationalize the IRAD method [2, 28, 29]. To do this, they suggested a DfHS method using two sequential methods. The first method [2, 29] proposed a Functional Reverse Engineering for Safety (FRES) approach underpinned by AD to obtain design feedback from knowledge of an existing system. The aim of FRES is to acquire the original intrinsic design and safety knowledge integrated in the functional models of existing systems (Figure 6). The proposed method can distinguish the components, design parameters and function requirements of an existing system and define the hazard related to each component, the design parameter and the functional requirement. Sadeghi et al. used product breakdown structure (PBS) [30] to represent the system components by the structural decomposition. To illustrate the interaction between this system component decomposition, the functional block diagram (FBD) has been used. This diagram highlights the fluxes existing between the elements of the product (contact, energy, matter, regard), and the external environments. The second method [28, 29] proposed a Functional RE-Engineering for Safety (FR2ES) approach using AD to define a system with good mechanical safety that is reliable and robust, and with few possible human errors. They used AD and failure mode and effect analysis (FMEA) to define a system with high mechanical safety as well as reliability and robustness.

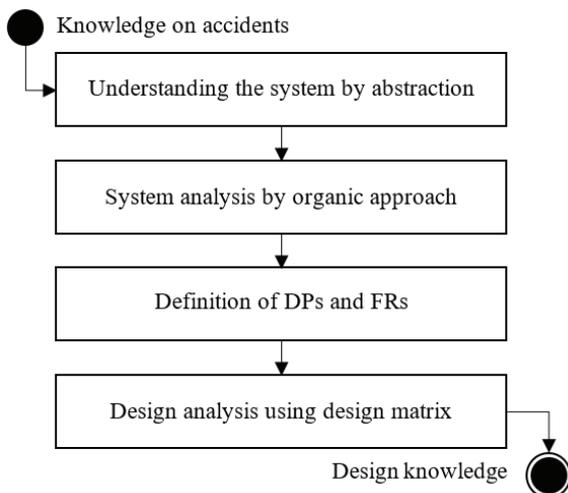


Fig. 6. Design knowledge extraction [29].

Sadeghi et al. [31] defined a safety indicator to assess the safety level. This indicator can measure safety from the conceptual design phase because, according to AD, a good design is a design with no coupling between the functional requirements. This consideration is included in the safety indicator. Reliability, which involves the life of the system, cannot be assessed in the embodiment design phase. It is also taken into account in calculating this indicator but is considered optimal in the conceptual design phase. Sadeghi et al. used two axioms of AD theory to calculate the influence of the system on hazardous event.

## 5 Discussion

### 5.1 Chronological discussion

As shown in Figure 7, the number of relevant papers published annually is not large, fewer than five before 2009. First research on application of AD in DfHS has been done ten years after introducing AD.

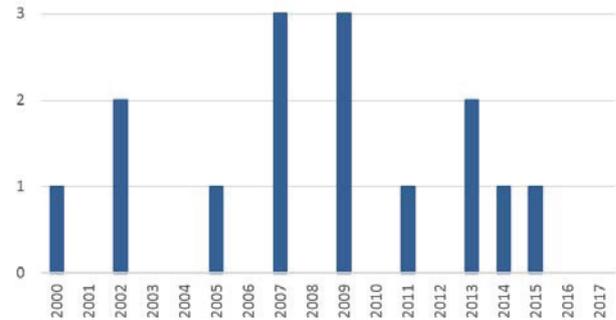


Fig. 7. Year of publications (till April 2017).

### 5.2 Thematic discussion

This paper summarises our findings based on our literature review of research on application of AD in DfHS. The results of this literature review are presented in Table 1.

Figure 8 shows how many of the DfHS works focus in specific the axioms of AD. The figure clearly shows that predominantly (60%) the both axioms are applied and deeper analysed. Approximately another 13% of the research papers involve first axiom of AD. Only few about 7% deepen their work also with the help of the second axiom. About 20% of researches have no focus on axioms of AD.

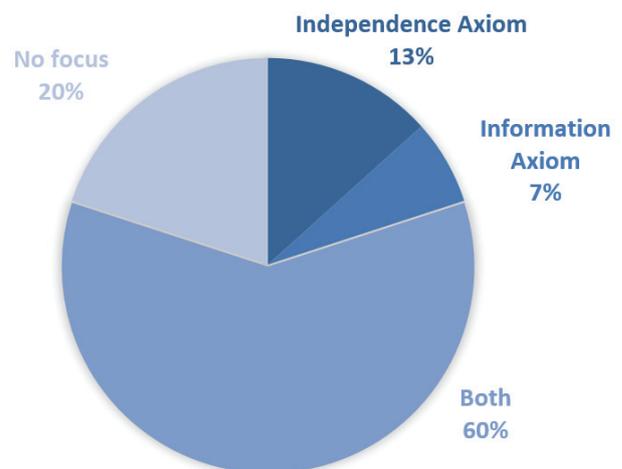


Fig. 8. Focus on axioms of AD.

**Table 1.** Application of AD in DfHS.

Author	Group		Focus on				Integration with others methods / tools	Application
	Ergonomic design	HCI	DfHS systematically	Independence axiom	Information axiom	Both axioms		
Helander & Lin [18]	✓					✓	-	Microscope workstation
Helander & Lin [19]	✓					✓	-	Microscope workstation
Helander & Jiao [20]	✓		✓				-	Usability testing
Karwowski [16]		✓				✓	-	Rear lighting system of an automobile
Heo & Lee [17]		✓				✓	FTA	Nuclear power plants
Helander [21]		✓				✓	-	Dual reservoir system
Lo & Helander [22]		✓				✓	-	Dual reservoir system
Ghemraoui et al. [23]			✓			✓	SA	Three-point hitch (TPH)
Ghemraoui et al. [24]			✓			✓	SA	TPH
Ghemraoui [25]			✓			✓	SA	TPH
Ghemraoui et al. [26]			✓			✓	SA	Dual knob faucet, Ski bindings
Sadeghi et al. [2]			✓	✓			SA FTA	Power take-off (PTO) drive shaft
Sadeghi et al. [28]			✓	✓			SA FMEA	PTO drive shaft
Sadeghi [29]			✓			✓	SA FTA FMEA TRIZ	PTO drive shaft & TPH
Sadeghi et al. [31]			✓			✓	SA FTA FMEA TRIZ	PTO drive shaft

### 5.3 Proposed roadmap for future DfHS works

The present paper aims to show how AD can contribute to human safety improvement in design process. Overall, the findings of the surveys and literature reviewed indicate that AD theory is more effective in the context of DfHS. This theory is useful in DfHS because of its capacity to present FRs and associated DPs, and includes criteria for evaluating designs. This method can be implemented at the conceptual design phase; so, FRs could be considered from the most early design phases by using this theory.

Among the research works reviewed that of Ghemraoui and her colleagues [23–25] and Sadeghi et al. [2, 28, 29] should be highlighted. Their proposal consists of a general suggestion for systematic risk identification and human safety integration in the early design phase.

As mentioned previously, in [31] the safety measured in terms of dimensionless quantities parameters. The safety measured based on hazard evaluation. But, expert opinions are often used to assess the hazards and probability of occurrence of risk in the context of DfHS. For future research directions, one path could be to investigate a method capable of taking into account uncertainties associated with expert judgements. To this, a database should store links of FR-DP-hazards. Categorization of mechanical hazards is not standardized thus, giving rise to confusion during design for human safety. The dimensions of a taxonomy for classification of hazard depend on the nature of the hazard (source of hazard) and the anatomy of accidents (consequence of hazard). To realize this link, hazards and more specifically source of hazards should be classified and standardized. To this, we can investigate on standard engineering components which use form features and support international standard for exchange of product data (STEP) formats. Therefore, to effectively integrate the hazards into the FR-DP, hazard should be embedded with STEP.

As a result, applying the methodology provides explicit safety knowledge related to design, as well as the relationship between this design knowledge and its corresponding design phase. This knowledge is based on the expertise and is essential for the future development of a software system that effectively provides necessary DfHS information to designers. This means providing information for each of the design phases without saturating designers with unnecessary information.

Recently, with combination of emerged technologies such as cloud computing, Internet of things, service-oriented technologies and high performance computing, a new manufacturing paradigm, named cloud manufacturing (CM), has been introduced. CM is known as a movement from production-oriented manufacturing to service-oriented manufacturing

In an ongoing research on DfHS, authors are developing an integrated, interoperable and collaborative platform to support DfHS using a service-oriented approach based on cloud computing paradigm. Considering the huge amount of different design and safety requests which should be fulfilled by this

platform, a structured solution for definition, execution and management of the services is essential. This can be achieved based on the AD theory. This solution insures a feasible structure of service execution to fulfill the safety agents' request. For further researches, one objective is to demonstrate how the AD theory can be used to support our cloud-based DfHS platform.

One idea is to recommend optimization of CBDfHS platform using the second axiom of AD. During DfHS, some constraints, such as lack of related information or devices, or some environmental constraints, don't allow designers to choose safer solutions. We need to consider the mapping between FRs, DPs and PVs over the time. For example, a smart vehicle is the most safe solution to prevent road traffic accidents, but a smart vehicle should be used in a smart city, and this constraint prevents to design smart vehicle. But in future, a smart city evolves and as a consequence smart vehicle could be designed and developed.

## 6 Conclusion

An overview and analysis of these studies were carried out based on (1) the author(s) name(s), (2) title of the paper, (3) the year of publication of each paper and (4) the title of the journal. This review identified 15 research topics that were clustered into three main research groups. The first group focused on the application of AD in ergonomic design. The second one focused on the use of AD in human computer interaction. The last group focused on integrating safety systematically in design process based on AD and systematic approach. AD is also used in safety evaluation during design process. AD appears to be more effective in the context of DfHS.

The results of this review provide a roadmap for our current research in DfHS in manufacturing systems and also vehicles. The review identified and discussed two gaps in application of AD in DfHS: A database should store links of FR-DP-hazards. In other words, the hazards should be effectively integrated with the FR-DP. For further researches, another objective is to demonstrate how the AD theory can be used to support our cloud-based DfHS platform.

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## Appendix: glossary

AD	Axiomatic Design
CM	Cloud Manufacturing
CBDfHS	Cloud-Based Design for Human Safety
DESA	Design Equations for Systems Analysis
DfHS	Design for Human Safety
DfX	Design for X

DPs	Design Parameters
FBD	Functional Block Diagram
FRES	Functional Reverse Engineering for Safety
FR2ES	Functional RE-Engineering for Safety
FRs	Functional Requirements
FTA	Fault Tree Analysis
FMEA	Failure Mode and Effect Analysis
HCI	Human-Computer Interaction
IRAD	Innovative Risk Assessment Design
PBS	Product Breakdown Structure
SA	Systematic Approach
TRIZ	Theory of inventive problem solving

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