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INTEGRATION OF HIGH-LEVEL DESIGN INFORMATION WITH AXIOMATIC DESIGN FORMULATION

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ABSTRACT

Axiomatic Design based design formulation (FRs-DPs mapping and the underlying Design Matrix) is the "meaning-base" of a design because it is human-intelligence-engaging (i.e., written in natural language), transparent (one can easily find out the rational behind the design), soft (one can easily propose modifications to improve the design), and evaluative (one can easily evaluate whether or not the design is a good or not-so-good one). To map FRs into DPs, or vise versa, however, knowledge and information is needed encoding the previous design trials, designers' engineering judgment, overall familiarity with the design problem, and alike. AI community has built up a tradition to use inductive decision trees, qualitative models, linguistic variables, and alike to capture the above-mentioned design-relevant knowledge and information. This study uses examples of decision trees, qualitative models, and linguistic variables, and examines the logical interactions of these formatted knowledge with the mapping process of FRs from a set of given DPs, and vise versa. It is found that a heterogeneous combination of deductive, inductive, and abductive reasoning is involved in the mapping process. Further study is needed in this direction. Nevertheless, AD based design formulation should accompany other information in a system for design to increase the trustworthiness, usability, and transparency of design-relevant information to individuals directly or indirectly involved in the design.

Keywords: Axiomatic Design, Knowledge Intensive Engineering, Natural Language, Inductive Learning, Linguistic Variable.

1 INTRODUCTION

Axiomatic Design (AD) has been introduced by Suh to guide human endeavor for better creation, i.e., better design [Suh, 1984]. AD assumes that a design involves a mapping between "what we want to achieve" and "how we propose to satisfy the 'what we want to achieve'". AD provides some well-defined terminologies, concepts, axioms, and guidelines [Suh, 1998] to help formulate a design in such a way that the designer knows exactly how well he or she is performing and if the performance is not satisfactory, then what should be done to improve the performance. For this AD is considered to be a methodological approach for designing artifacts and has already been found useful in many areas of design, such as software design, materials design, structures design, products design, computer integrated systems design, and so on. See for instance [Kim, 1991; Suh, 2001; Chen and Feng, 2004; Lee et al., 2003; Su et al., 2003; Jang et al., 2002; Chen et al., 2001] and the references therein. To facilitate the application of AD software tools are needed (e.g., Acclaro Designer^{TM}, http://www.axiomaticdesign.com). It is argued that different kind of design-relevant information should be integrated with such software tools to enhance the performance [Lipson and Suh, 2000; Chung and Suh, 2002; Tomiyama, et al. 2003].

The goal of this paper is to highlight the ways that AD based design formulation and design-relevant information interact with each other. The remainder of this paper is organized as follows. Section 2 discusses why and how AD based design formulation serves as the "meaning-base" of a design. Section 3 shows how the design-relevant knowledge and information influences the meaning-base of a design (i.e., influences AD based design formulation). Section 4 explains how the meaning-base of a design logically evolves in presence of such structured knowledge as decision trees, qualitative models, and linguistic variables. This in turn helps identify the layout of a better-engineered system for designing artifacts. Finally, and before concluding the paper, a discussion is provided pointing out the outcome of this paper from the design research viewpoint, in general.

2 MEANING-BASE OF A DESIGN

Although the integration of Database (DB) and Knowledgebase (KB) with other design aids has been studied from the context of developing better-engineered systems for design, they are not enough to complete a system of design. The "Meaning-Base" (MB) of a design should accompany the other modules. Once the MB is missing, then the complexity in dealing with design-relevant information increases in an unpredictable manner. Naturally, the question is which piece of information should be considered the MB of a design? The general answer is that a MB of a design is a piece of information which provides the rationale behind the design, which is essentially easy-to-interpret, from which other individuals than the designer can understand what should be done to improve the design, and likewise. As such, there is a high correlation between MB and AD. Let us elaborate this issue further.

The essential ingredient for designing creative and novel artifacts is human intelligence. And, in order to help apply human intelligence efficiently and effectively it is highly recommended that the design formulation uses a natural language because the natural languages are the manifestation of human intelligence [Kobayashi and Sugeno, (2001)]. The correlation between natural languages and human intelligence is considered the results of the following reasons. 1) If a proposition is expressed and stored using a natural language it is easy to process by a human being. 2) If a proposition is expressed by using a natural language then a human being can easily formulate a strategy to understand the meaning of the proposition. 3) Such human intellectual activities as planning, reasoning, and creativity are performed well by the use of natural languages than performed by the use of any other forms of information. Therefore, to facilitate the application of human intelligence while designing artifacts, linguistic design formulation (LDF) is the recommended formulation. If LDF exhibits the following characteristics, then it can be considered a MB of a design. 1) *Transparency*—one can easily find out the rational behind the design. 2) *Softness*—one can easily propose modifications to improve the design. 3) *Valuation*—one can easily evaluate the design and can easily extract knowledge.

In AD, a design is formulated (i.e., FRs-DPs mapping and Design Matrix) by using linguistic propositions [Suh, (1998); Ullah, (2003)]. Therefore, AD based design formulations are LDF. Seeing the FRs and DPs mapping one can understand the rational behind the design. Therefore, AD based LDF exhibits the characteristics of Transparency. In addition, seeing the relationship between FRs and DPs (i.e., Design Matrix) one can readily evaluate the design (whether or not the design is an uncoupled, coupled, or decoupled design). This means AD based LDF exhibits the characteristics of Softness. Moreover, seeing the Design Matrix one can seek modifications to improve the design by simply suggesting new FRs or DPs with no coupling or by simply readjusting the number of FRs and DPs to remove the redundancy. This means AD based LDF exhibits the characteristics of Valuation.

In synopsis, due to the involvement of natural languages in formulating a design using AD and due to AD's ability to make a distinction between a set of good and not-so-good designs, AD based design formulation serves as the MB of a design.

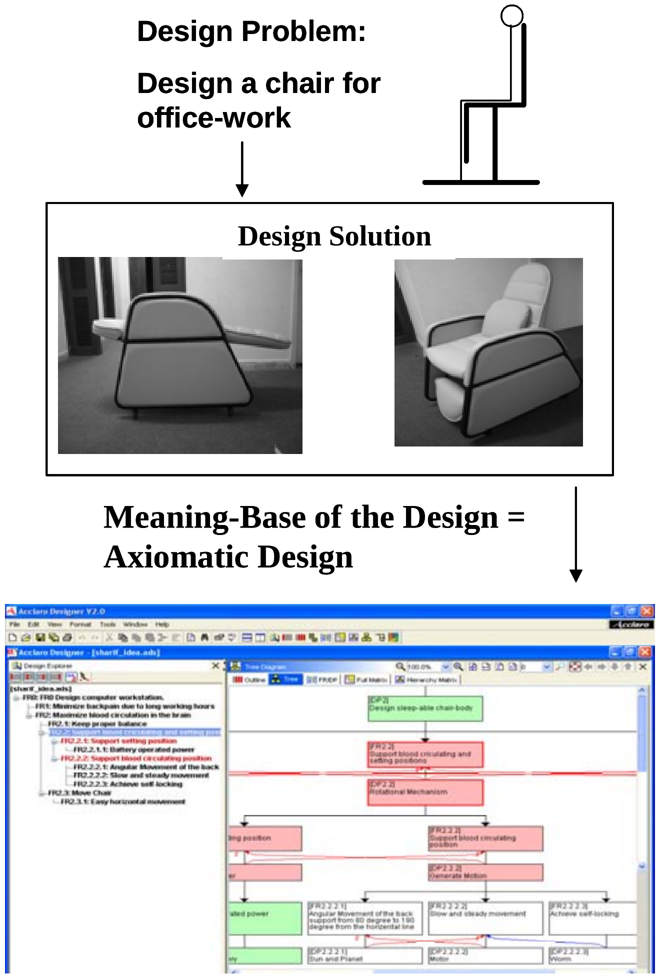


Figure 1. Meaning-base of a chair for office-work [Rashid, et al. (2003)].

To realize AD's role in constructing the MB of a design more deeply, consider the design problem shown in Figure 1—"design a chair for office-work" [Rahid, et al. (2003)]. This problem can be solved in many different ways. However, what are the preferences of the designers are readily understood by a wide spectrum of individuals directly or indirectly related to the design project mainly because of the fact that the FRs-DPs mapping uses natural language (English). From this mapping one can also easily evaluate the whole or a part of the design (coupled or uncoupled or decoupled, or redundant design), one can suggest modifications to improve the design (suggest uncoupled design if coupled or decoupled), and so on. This means that the coexistence of AD based design formulation and design solution increases the trustworthiness of the design-relevant information to others, which is perhaps the most important role of a MB.

3 ROLE OF KNOWLEDGEBASE

It is proposed in the above section that FRs-DPs mapping provides the MB of a design. However, AD does not precisely define the process of deriving a DP from a predefined FR or vise versa. It just mentions that the process of zigzagging produces FRs and DPs, where zigzagging is not precisely defined. As such, the process of mapping FRs and DPs itself depends solely on the creativity of the designer [Lossack, (2002)]. When a design process [Pahl and Beitz, 1996; Yousef, 2003] is considered in between the function and physical domains, there are other important issues that need consideration for developing a better-engineered software tool for practicing AD. Particularly, the issue of KB is very important because a KB substantially influences the process of mapping FRs from DPs or vises versa. See [Tomiyama, et al. 2003] to realize how FRs-DPs mapping depends on the knowledge of a designer, i.e., on the supplied KB. AD community has also acknowledged the contribution of knowledge in FRs-DPs mapping—see, for instance [Lipson and Suh, 2000; Chung and Suh, 2002].

However, the main theme of continuing a design process using a KB is formally known as "synthesis"—a process of integrating low-level building blocks for achieving a given arbitrary high-level functionality [Tomiyama, 1994; Shimomura, et al. 1998; Kota, 2003; Antonsson and Cagan, 2001]. From the formal logic viewpoint, synthesis encompasses all three logical modes of reasoning: deduction, induction, and abduction, as shown in (1).

$$\begin{aligned}
&\text{Axiom or Rules} \cup \text{Facts} \xrightarrow{\text{Deduction}} \text{Theorems} \\
&\text{Facts} \cup \text{Theorems} \xrightarrow{\text{Induction}} \text{Axioms or Rules} \qquad (1) \\
&\text{Axioms or Rules} \cup \text{Theorems} \xrightarrow{\text{Abduction}} \text{Facts}
\end{aligned}$$

Particularly, to come up with a creative design, abduction should dominate other modes. The reason is abductive reasoning helps integrate knowledge of various domains and find new facts, which is not possible to generate if someone confines himself or herself to a specific domain of knowledge [Tomiyama, et al. 2003]. Remarkably, abduction cannot be performed independently; the outputs of deduction and induction are needed directly to perform abduction, as it is shown in Figure 2. Alternatively, applying abduction may not have to be as straightforward as it is shown in Figure 2. The precise logical nature of abduction is not known yet [Schurz, 2002].

From the design point of view, however, it can be said that there should be a chance to perform "critical thinking" (i.e., any combination of deduction, induction, and abduction) in the presence of KBs. The intension is to generate a MB with more informative FRs and DPs so that one can apply the Information Axiom (minimize information content of a design) easily to optimize the design.

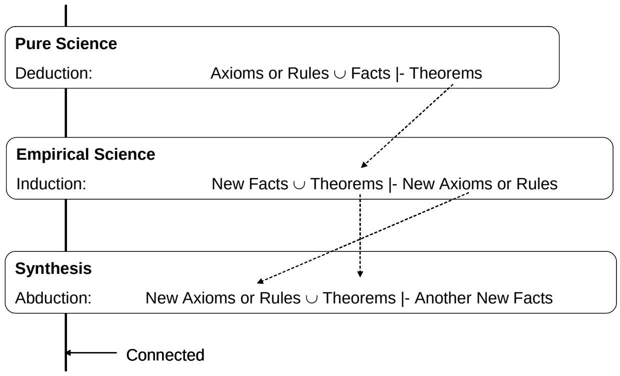
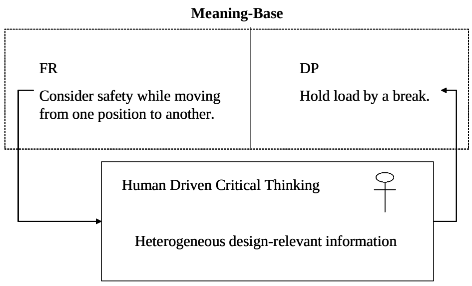
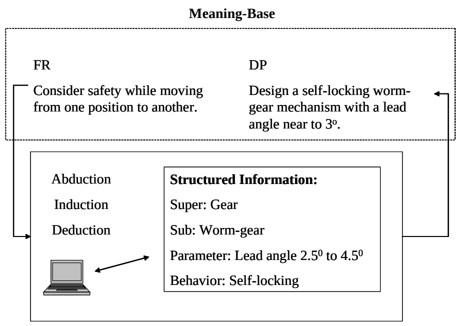


Figure 2. Integrated logical reasoning modes.



(a) *human-driven design process*



(b) *computer-aided design process*

Figure 3. Design process and meaning-base.

See Figure 3, for instance, to realize how critical thinking may (or should) affect MB of a design (i.e., FRs-DPs mapping). Compare the DPs shown in Figures 3(a) and (b). DP in Figure 3(a) (hold load by a break) is less informative compare to that of in Figure 3(b) (design a self-locking worm-gear set with a lead angle near to 3^0). It would be easy to apply Information Axiom with the DP in Figure 3(b). Suggesting a DP from a piece of formatted knowledge is perhaps abduction (i.e., critical thinking), as it is understood from the case in Figure 3(b). However, constructing such a piece of formatted knowledge is the results of deduction or induction or combination of them. This will be cleared after going through the next section.

4 INTEGRATION OF DB, KB, AND MB

Upon clarifying the MB of a design and the role of KB in design, it is time to propose a system to integrate them all. One of the possible systems is shown in Figure 4. It is needless to mention that the main constituents of the proposed system are DB, KB, and MB. AD based FRs-DPs mapping plays the role of MB, which is the novelty of this system. The MB is constructed using structured information stored in KB; abduction plays the important role here, as it is mentioned in the above section.

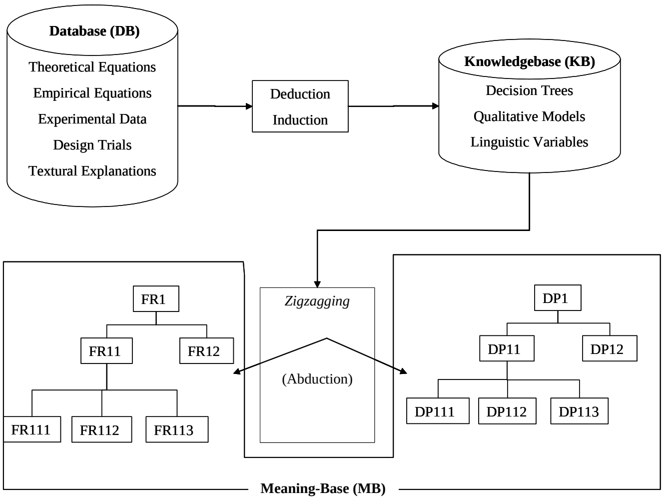


Figure 4. The proposed design system.

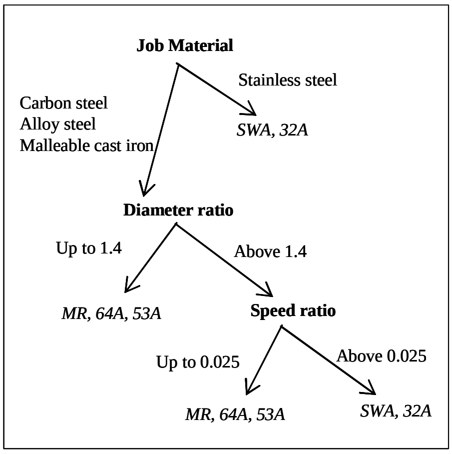
To construct the KB data is needed which comes from the DB. Deduction and induction plays important role in constructing KB, i.e., in formulating the knowledge. For example, inductive learning (induction) [Quinlan, 1986] has extensively been used to analyze design-relevant data and extract knowledge (i.e., find classes or patterns in a given set of data) [Ullah, 1999; Stahovich and Bal, 2002]. The extracted knowledge is expressed by using decision trees (a directed binary graph with open leaf node). Because the decision trees are learned from the previous design trials, the designer's engineering judgment, knowledge of implicit constraints, design strategy, they are very helpful in assisting novice designers. Another machine learning technique known as qualitative models [Forbus, 1996] are also playing an important in extracting knowledge from empirical or scientific facts [Bratko and Suc, 2003]. However, in some cases there is an uncertainty in expressing the data points itself. In this case, granular information can be used to extract knowledge from uncertain or vaguely defined data. One of the popular techniques is the linguistic variable of Zadeh [Zadeh, 1975; Ullah, 2002; Ullah and Monnet 2002; Ullah, 2004] which puts vaguely defined data points in a (many-valued) logical setting for formal computation. The remainder of this section shows how the MB evolves by the use of decision trees, qualitative models, and linguistic variables.

Consider the KB shown in Figure 5, which are two decision trees of grinding wheel knowledge constructed by using the data of past design experiences of grinding wheel [Ullah, 1999]. Suppose that a designer is going to design a grinding wheel for super surface finish of a stainless steel job. Therefore, FR = "*Design a grinding wheel for stainless steel machining with super surface finish*". If this FR is fed into the decision trees (DT1 = abrasive type, DT2 = grain size, in Figure 5), then a logical search can be carried out to formulate the DP. This search is to find the leaf nodes of DT1 and DT2 so that the attributes (A) job material and surface finish match with that of the above FR. This search process is as follows:

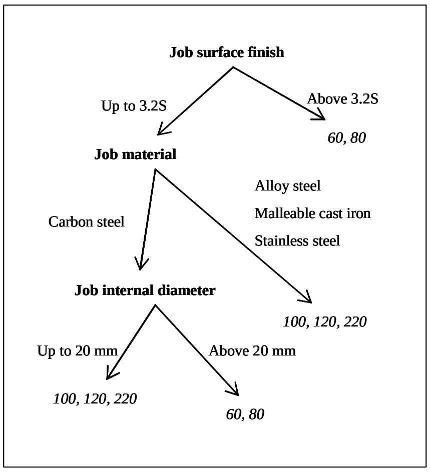
Input	$\forall i \bullet \text{Atom}(i) \models \text{FR}$ KB = $\forall j \bullet \text{DecisionTree}(j) = \langle \ldots, \text{Branch}(j,k) = \langle \ldots, \text{Node}(j,k,l), \ldots, \text{Leaf}(j,k) \rangle, \ldots \rangle$
Define	$\forall i \bullet \text{Atom}(i) \in \text{Proposition}(i)$
Process	$\forall \text{Node}(j,k,l)$ $\exists i \bullet \text{Node}(j,k,l,\neg\text{Proposition}(i)) \bullet \text{DecisionTree}(j) = \langle \ldots, \text{Delete}(\text{Branch}(j,k)), \ldots \rangle$
Output	$\forall \text{Node}(j,m,n)$ $\exists i \bullet \text{Node}(j,m,n, \text{Proposition}(i)) \bullet \text{DP} := \text{Leaf}(m,n)$

The above search process yields DP = "*Design grinding wheel with abrasive type SWA or 32A; grain size 100, 120, or 220*". This DP is highly informative, i.e., it contains information of two essential parameters of a grinding wheel, other than the information of hardness grade, structure, and bond type. Using this DP one can evaluate grinding wheel alternatives and find the optimal one based on Information Axiom (minimize the information content of the design).

Qualitative models [Forbus, 1996] can also be expressed by using decision trees. One special feature of the qualitative models is that they use monotonic functions at the leaf nodes of a decision tree. For example, $V1 = M^{-,+}(V2, V3)$ is a monotonic function that expresses that the variable V1 monotonically decreases with the increase in variable V2 but monotonically increases with the increase in the variable V3. Among other uses of these models, they are helpful in capturing the control strategy of electromechanical systems qualitatively [Bratko and Suc, 2003]—an essential part of modern engineering systems. While proposing the MB of an electromechanical system, one can consult the qualitative models of the control strategy and derive FRs and DPs to design the control subsystem. Consider, for example, the case shown in Figure 6 [Bratko and Suc, 2003]. The case of Figure 6 is a qualitative model of a control strategy of an operator. If this control strategy is taken as the KB following design formulation can be fund obvious.



(a) abrasive type



(b) grain size

Figure 5. Two decision trees for grinding wheel design [Ullah, 1999].

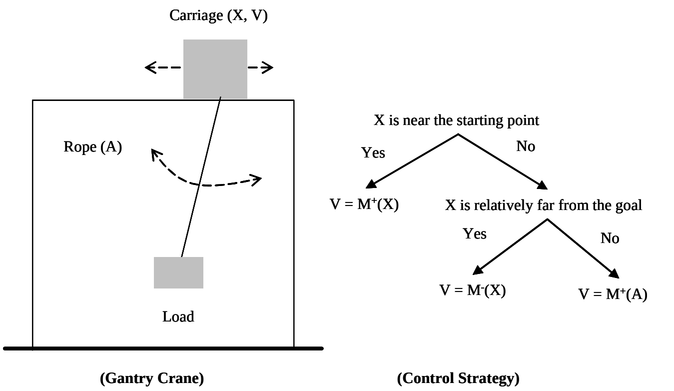


Figure 6. Qualitative control strategy [Bartko and Suc, (2003)].

FR Control the carriage safely and efficiently

DP Control velocity and angle of swing relative to distance from starting point and goal.

FR1 Increase the velocity when the carriage is near the staring point.

FR2 Decrease the velocity when the carriage is relatively far from the goal.

FR3 Increase velocity to control the swing angle

DP11 sense distance near to starting point

DP12 Accelerate

…

Logically, the zigzagging, i.e., to get DP1, FR.1, FR.2, FR3,…, successively, can be explain as follows:

Input Process Output	FR, KB = DT ∀Branch(.)∈DT |= DP DP
Define	Start(.), Goal(.), Small(.)
Process	∀x∈{|Small(X)-Start(X)|}•Branch(x)•Leaf(Branch(x)) Leaf(Branch(x)) |=FR1
Output	FR1
Process	∀x∈{¬{|Small(X)-Start(X)|}∧¬{|Small(X)-Goal(X)|}}•Branch(x)•Leaf(Brach(x)) Leaf(Branch(x))|=FR2
Output	FR2
Process	∀x∈{|Small(X)-Goal(X)|}•Branch(x)•Leaf(Branch(x)) Leaf(Branch(x)) |= FR3
Output	FR3
...	…

Another KB that is as equally important as the decision trees and the quantitative models is Linguistic Variable (LV) [Zadeh, 1975]. A linguistic variable LV is a quintuple, i.e., LV = (L, T(L), U, G, M). In LV, L = name of the variable, T(L) = linguistic terms (labels of fuzzy subsets), U = universe of discourse (points of interest), G = a syntactic rule (could be null), M = a set of normalized membership functions (semantic rules) to define the labels in T(L). Particularly, LV is useful means to formulate a KB when there is an uncertainty in expressing data one a specific issue, there are disagreements among various sources of information, and there is a lack of information. An individual subjectively construct the LV on an issue under consideration. Consider, for example, the LV shown in Figure 7 for a self-locking device. Note that the different sources provide different kinds of qualitative and quantitative information on the self-locking mechanism. This heterogonous information is extracted to form a KB with only one LV. This LV consist of L = self-locking or load-holding devices; T(L) = {dynamic load with lubrication, static load with lubrication, load without lubrication or extra break}; U = [lead angle of worm-gear set 0 degree to 14 degree]; G = α-cut (a process to get a crisp set from a fuzzy subset in U); M = three triangular/trapezoidal membership functions for all members in T(L).

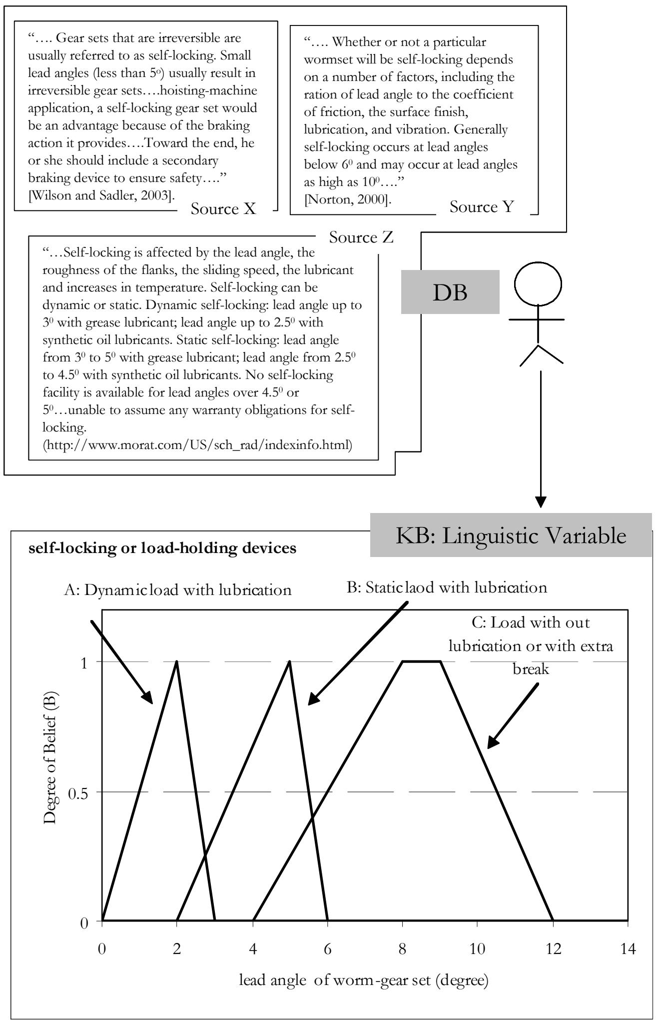


Figure 7. Linguistic variable for self-locking devices.

Such a LV can be logically computed to construct the MB of a subsystem for safety, as follows.

Input Proces s Output	FR0, DP0, KB = LV(L, T(L), U, G= α-cut, M) LV(L) |= FR1 FR1
Proces s	∃x•LV(U(x))•DP1(U(x))
Output	DP1
Proces s	∃y•LV(T(L(y)))•FR11(T(L(y)))
Output	FR11
Proces s	FR11•LV(M(FR11))•∃α∈(0,1]•M(FR11(G(α))) |= DP11(M(FR11(G(α)))
Output	DP11

There are many possibilities of MB, according to the above logical operations applied to the KB in Figure 7. One of the possible MBs is as follows:

FR0	Consider safety
DP0	Design a load holding device
FR1	Design a self-locking mechanism
DP1	Design worm-gear set with lead angle within 14 degree
FR11	Design for static load with lubrication
DP11	Keep lead angle within 3.5 degree to 5.5 degree

Note that the final DP (i.e., DP11) is going to facilitate the application of Information Axiom due to the presence of a well-defined range of lead angle of a worm-gear set.

5 DISCUSSIONS

The findings of different studies aiming at understanding the designers' involvements in dealing with design-relevant clearly indicates that MB of a design has been a key issue, although it has not been directly pointed out as it is done in the present study. For instance, consider the findings of [Marsh, 1997; Clarlton, 1998; Blessing and Wallace, 2000; Ahmed, et al. 2003]. According to these studies, the major part of design-relevant information is obtained through personal contacts involving two or more individuals because of the low trustworthiness of accessed or available information. To overcome from this uncertain human involvement it is recommended that both design object data and design process data should be indexed and stored together. It is also found that the proper utilization of design-relevant information does not depend only on the quality of the information but also on the intellectual ability of a designer. The present study clearly shows that to increase the trustworthiness and transparency (of design-relevant information) and to store the design object and design process data together, AD based design formulation (i.e., FRs and DPs mapping) should accompany other design-relevant information. In other words, AD based design formulation is the MB of a design. This way the present study has identified a novel characteristic of AD. This characteristic is going to increase the use of AD in developing better-engineered design tools.

Another important result that the present study reveals is that the correlation between knowledge intensive design and AD. Structured domain knowledge is necessary to continue to the process of building the MB (i.e., gradually expand the tree of FRs and DPs) [Tomiyama, 2003]. The problem here is actually to relate a known function to the unknown structures that instantiate it, or to relate a known structure to the unknown function that it supports. Computational synthesis (any combination of logical reasoning, deduction, induction, and abduction) plays an important role here. Although the present study has showed how to derive FRs and DPs from such structured knowledge as decision trees, qualitative models, and linguistic variables, the logical operations involved are heterogeneous in nature (not clearly abduction, deduction, or induction). This happens partly because of the way the information is indexed (see the indexing of the decision trees of grinding wheel and control strategy in the previous section), partly because of the forms of information (crisp or granular, see the example of self-locking mechanism in the previous section), or partly because of the precise logical nature of synthesis is not yet clearly known (see (Schurz, 2002]). To find out the precise logical nature of the act of combining building blocks to achieve increasingly complex functionality (i.e., synthesis), it is important to study the activities of biological systems [Lossack, 2002; Garibay, 2003] because synthesis is universal phenomenon of all biological systems, particularly, DNA-RAN-Protein interaction or central dogma). Therefore, the symbiosis between central dogma inspired computational methods [Ullah, 1999; Ullah, 2003, Garibay, 2003] and AD based design formulation in presence of formatted KB could be a productive approach in revealing better-engineered software tools for design. In realizing such software tools agent based technology is going to be an essential means to integrate DB, KB, and MB [El-Khatib et al., 2002]. Nevertheless, ample theoretical and applied research opportunities lie ahead centering AD and knowledge intensiveness of design.

6 CONCLUSIONS

This study clearly points out that due to the use of a natural language in formulating the FRs-DPs mapping, and due to its ability (FRs-DPs mapping) to make a clear distinction between set of good and not-so-good designs, AD based design formulation serves as the meaning-base of a design, which, in turn, enhances the trustworthiness and transparency of design-relevant information to all directly or indirectly involved with a design project. On the other hand, the process of mapping FRs into DPs, or vise versa, is a function of designers' knowledge and creativity, i.e., previous design trials, the designers' engineering judgment, knowledge of implicit constraints, design strategy, qualitative, and overall familiarity with the design problem. Such design-relevant knowledge and information can logically be expressed by inductive decision trees, qualitative models, linguistic variables, and alike. The present study has examined the logical interactions of the above-mentioned formatted knowledge in deriving FR from a given DP and DP from a given FR. The logical patterns in this interaction found so far are seemed to be a heterogeneously combination of deductive, inductive, and abductive reasoning. Nevertheless, the design system proposed in the present study that integrates Database, Knowledgebase and AD based FRs-DPs mapping is a productive system for investigating better-engineered software tools for design.

7 ACKNOWLEDGEMENTS

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