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Methods for Measuring Customer Satisfaction in the Design Process

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Abstract: *In the design process, the designer makes decisions under uncertainty, contradiction and ignorance conditions. Are these decisions correct and to what extent? How much do they influence customer's satisfaction? These are only some of the questions the designers face all time. These dilemmas appear more in early phases of the design process.*

The explicit objectives of this paper is improvement of design decision making process in such a way that in same time when designer made a decision he or she show result that decision on customer satisfaction. In order to solve above problems, the paper describes the method, which enables integrated use of the axiomatic approach to designing, and the Taguchi method of robust design. This approach implies the modelling of the development process as an evidence-reasoning network based on uncertain evidence described via belief functions of (Dempster - Shafer theory).

The paper starts with base concept of belief functions and valuation based system or evidential reasoning system for representation and reasoning based on uncertainty. After that we introduce coefficient of relative decrease of uncertainty in design process and new graphical representation of system architecture - the evidence networks. On the end we presents a method for measuring customer satisfaction in the design process in uncertainty condition using evidence networks.

Keywords: *axiomatic design, belief functions, Taguchi, evidential network*

1. INTRODUCTION

Market globalization and customer satisfaction dramatically change manufacturing philosophy by promoting advance production concepts based on new design theory approaches.

Quality requirements have to be built into the product in its development phase. This implies that all development activities are guided and evaluated by customer's needs, requirements and expectations. Product and manufacturing design must be completed as fast as possible. Design solutions should be robust to all disturbances in the workplace where the product is manufactured and where it will be used.

In the development phase, the designer makes decisions under uncertainty, contradiction and ignorance conditions. Are these decisions correct and to what extent? How much do they influence customer's satisfaction? These are only some of the questions the designers face all time. These dilemmas appear more frequently in early phases of the development process.

In order to solve above problems, the paper describes the method that enables measuring customer satisfaction in the design process. The method based on integrated use of the axiomatic approach to designing [Suh (1990), (1995)] and the Taguchi method of robust design [Byrne and Taguchi (1987)]. This approach implies the modeling of the design process as an evidence reasoning network [Shenoy (1998); Xu and Smets (1995)] based on uncertain evidence described via belief functions of Dempster - Shafer theory [Shafer (1976)].

2. THEORY OF BELIEF FUNCTIONS

Assessing a specific situation from the real world is often based on ambiguities, contradictions and ignorance. The information can come from various sources: from the experience of individuals, from the signals registered by specific sensors, from the contents of published materials, etc. Such evidence can rarely be clearly distinguished; it is often incomplete, ambiguous in its meaning and erroneous.

Uncertain evidence is not easily represented by a logical formalism. The use of classical probability methods requires entirely complete evidence, i.e., approximately correct specification of probability parameters, which implies statistical data on a large number of cases or experiments. Since we are not always able to satisfy these conditions due to various reasons, we turn to different solutions.

Theory of belief function or Dempster-Shafer's (D-S) theory provides powerful tools for the mathematical representation of subjective uncertainties. Namely, it is an intuitively adapted formalism for reasoning below the uncertainty level. In terms of mathematics, this theory represents the generalization of Bayes' conditional probability theory.

2.1 Belief function - the basic concept

Model of the belief function consists of variables, their values and the evidence, which supports them. Variables represent specific questions regarding to aspect of the problem under consideration. Given questions are answered using data originating from various sources, i.e., from context of published papers, from measurement data, from expert opinions, etc. Fully integrated support to the sought answer is called evidence.

Evidence can be represented by belief functions, which are defined as follows:

Definition.1. [Xu and Smets (1995)] Let Θ be a finite nonempty set called the frame of discernment, or simply the frame. Mapping *Bel*: $2^{\Theta}\rightarrow[0,1]$ is called the (unnormalized) belief function if and only if a basic belief assignment (bba) *m*: $2^{\Theta}\rightarrow[0,1]$ exists, such that:

$$\sum_{A\subset\Theta} m(A)=1 \qquad (1)$$

$$Bel(A)=\sum_{B\subset A, B\neq \emptyset} m(B) \qquad (2)$$

$$Bel(\emptyset)=0 \qquad (3)$$

Assignment *m*(A) can be viewed as the measure of belief which corresponds to subset A and takes values from this set.

Condition (1) (Eq. 1) means that one's entire belief, supported by evidence, can take the maximum value 1, and condition (3) (Eq. 3) refers to the fact that one's belief, corresponding to an empty set, must be equal to 0.

Value *Bel*(*A*) represents the overall belief corresponding to set A and all of its subsets.

Each subset A such that *m*(A)>0 is called a focal element.

The empty belief function is the function which satisfies *m*(Θ)=1, and *m*(A)=0 for all subsets of *A*≠Θ. This function represents total ignorance about the problem under consideration.

2.2 Valuation Based Systems – VBS

Valuation Based Systems - (VBS) is the abstract framework proposed by Shenoy for representation and reasoning based on uncertainty [Shenoy (1989)]. It supports the representation of uncertain knowledge of various domains, including the Bayessian probability theory, Dempster - Shafer evidence theory based on belief functions, and the Zadeh-Dubais-Prade possibility theory [Xu and

Smets (1995)]. Graphical representation of a VBS is called the valuation network.

VBS consists of a set of variables and a set of valuations defined on subsets of these variables. The set of all variables is denoted by **U** and represents the space of the problem under consideration. Each variable represents a relevant problem aspect. For every ***Xi***, Θ_{Xi} denotes the set of possible values of the variable, which is called the frame of ***Xi***. For A (|A|>1) a subset of **U**, the set of valuations defined on ΘA represents relationships between variables of A. Frame ΘA is the Cartesian product of all Θ_{Xi}, for ***Xi*** in A.

Knowledge represented by this valuation type is called generic or general knowledge, and can be represented as a knowledge base within expert systems. **G** denotes the set of all subsets on which such a valuation is defined.

Valuations on single variables are also defined in the VBS, representing the so-called factual knowledge constituting the database of expert systems. **F** denotes the set of variables on which such valuations are defined.

An expert defines the general - generic knowledge for a problem. This knowledge is not modified in the reasoning process. The factual knowledge will be modified according to the status of the problem under consideration. These two knowledge types have the same treatment within the VBS. **H=GUF** denotes the set of all subsets on which the valuation is defined. In this paper, valuations are represented by belief functions. A VBS system supporting processing of uncertain knowledge described by a belief function is called an **Evidential Reasoning System** or the **Evidence System,** and valuation networks are called **Evidence Networks (EN)** [Xu and Smets (1995)].

The purpose of evidence based reasoning is the evaluation of hypotheses when the actual evidence is given (factual knowledge). This is performed by evaluating valuation networks in two steps.

Combination of all belief functions in the evaluation network, resulting in the so - called global belief function.

Marginalization of the global belief function to the frameworks of each particular variable or to subsets of variables, resulting in marginals for each variable or variables subset.

3. USING UNCERTAIN EVIDENCE IN THE DESIGN PROCESS

Designers create design solutions based on their intuition, experience and insight into existing solutions or insight into data, which assist them in deciding for the right version. The information can have various sources, earlier design solutions, analyses, calculations and/or experience of relevant domain experts. There is a problem here how to include such evidence into the design process, i.e., how to enable the designers to exploit it in their work. The entire problem should be viewed through the magnifying glass of contemporary computer integrated manufacturing systems.

Another problem is related to the above - how to use in this way included evidence in the design process to make relevant conclusions on the subject whether the proposed design solution is satisfactory or not.
The answer to the first question is given by the theory of belief function, which enables that any evidence can be expressed mathematically through a set of belief functions.

The solution of the second problem is presented in [Djapic and Milacic (1995)]. This approach is based on the generalization of the concept of entropy applied to the set theory, i.e., on the belief entropy as a measure of the belief uncertainty emitted by a knowledge source.

The approach is based on the following. The evidence of a knowledge source is expressed by belief functions. Also, it is possible to determine the value of its belief entropy.

In order to assess a problem, it is not enough to hear an opinion i.e., to use evidence from just one knowledge source. At least one more knowledge source with particular belief is needed to confirm the statement.

Now we have two independent knowledge sources and the evidence from both of them supports the possible answers to questions related to the problem we are trying to solve. It is possible to determine the belief entropy of these jointly observed knowledge sources (pre-consensus state). The theory of belief function i.e., Dempster's rule, enables us to combine the evidence from both knowledge sources expressed by the belief function and in this way obtain a new belief function for which it is also possible to determine the belief entropy (post-consensus state).

In [Djapic and Milacic (1995)] coefficient was suggested to quantify the decrease of uncertainty (confusion) in someone's belief that is seeking an answer to the question X and has the information coming from both sources. That coefficient (Fig. 1) is not qualified, it is monotonously ascending and its value is between 0 and 1.

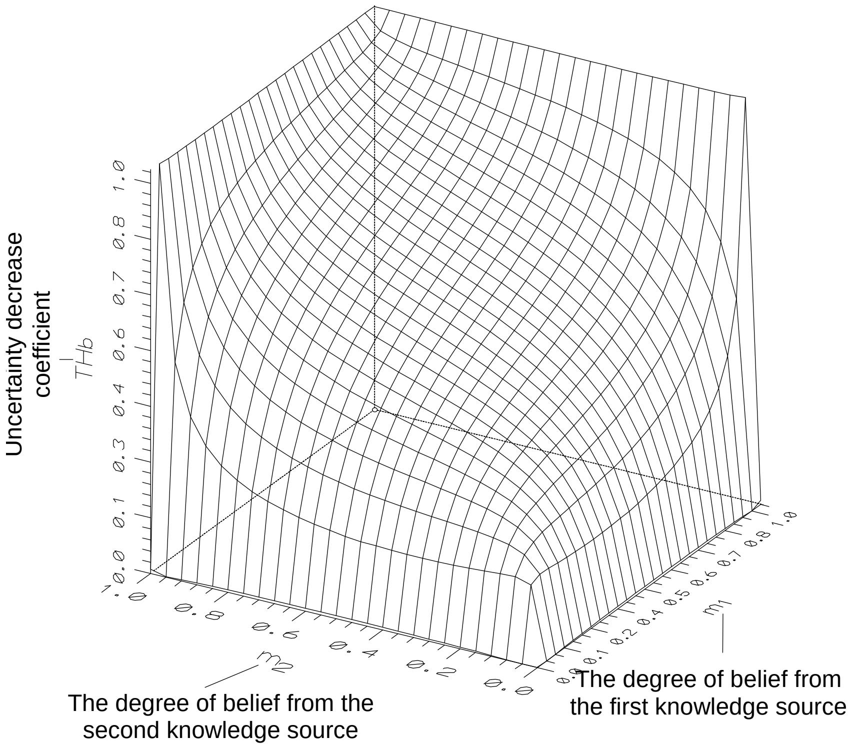

Figure 1. Coefficient of relative decrease of uncertainty [Djapic, Milacic, (1995)]

4. REPRESENTED SYSTEM ARCHITECTUTE AS AN EVIDENCE NETWORK

Axiomatic design theory defines design as the creation of solution for some problem in the form of product, processes or systems that satisfy perceived need through mapping between functional requirements (FRs) and design parameters (DPs) [Suh (1990), (1995)]. It provides a systematic and science base for making decision through design process. The basic concepts of this theory are (1) domains (customer requirement; functional requirements; design parameters and process parameters), (2) design hierarchy, (3) zigzag mappings and (4) and (5) first and second axiom.

The goal of any project can be presented as a single functional requirement (FR). This FR is addressed by single design parameter (DP) which represented “how is this project goal accomplished”. Through a process of decomposition, each design parameter is broken down into constituent sub-FRs with corresponding sub-DPs. This process is known as zigzagging, continues top-down through to the DPs which can be physical realization. The hierarchical structure, which is crated in this way, is known as system architecture [Hintersteiner and Friedman (1999)].

System architecture represents tool for decision making and its documentation in axiomatic design. It captures the requirements (FRs), components (design parameters DPs) and their relationships. [Tate (1999)].

In [Djapic (2000)] and [Djapic and Milacic (2000)] is proposed a new graphical representation of system architecture - the evidence networks developed to enable knowledge and reasoning representation under the conditions of uncertainty. Uncertain evidence is described by belief functions in the evidence network.

The strength of the evaluation network concept lies not only in the graphical representation of system architecture, but also in the fact that it (1) enables reasoning (inference) under conditions of uncertainty, and (2) enables graphical combination of various design domains as shown in Fig. 2. Design equation can be represented via belief function (Eq. 4)

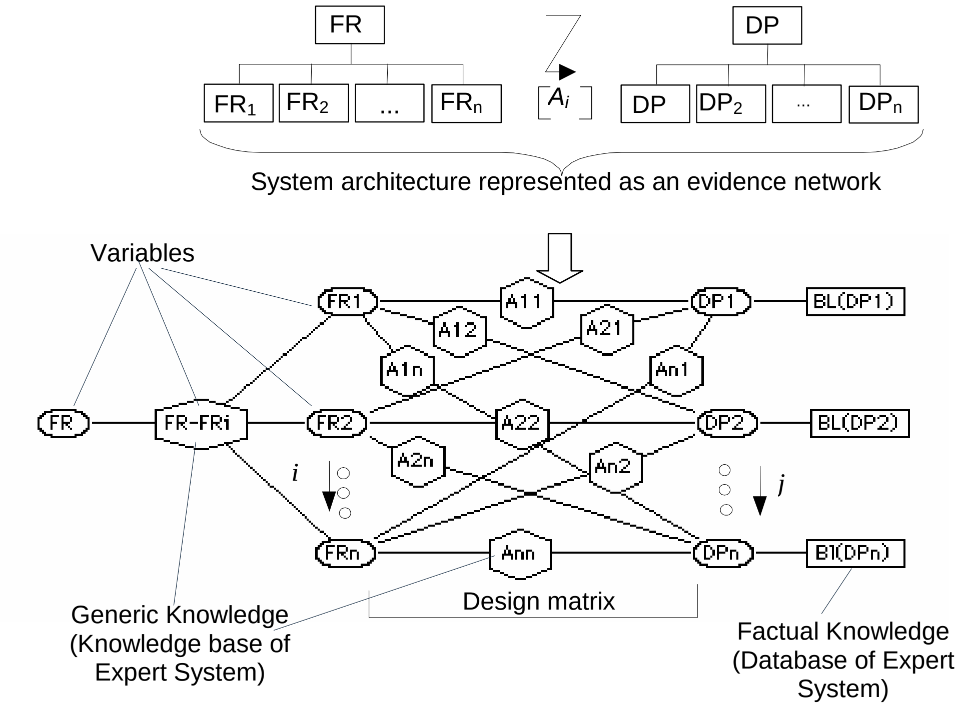

Figure 2. System architecture represented as an evidence network [Djapic (2000)]

$$\begin{Bmatrix} FR_1 \\ FR_2 \\ \dots \\ FR_i \\ \dots \\ FR_n \end{Bmatrix} = \begin{bmatrix} Bel(A_{11}) & Bel(A_{12}) & \cdots & Bel(A_{1j}) & \cdots & Bel(A_{1n}) \\ Bel(A_{21}) & Bel(A_{22}) & \cdots & Bel(A_{2j}) & \cdots & Bel(A_{2n}) \\ \vdots & \vdots & \ddots & \vdots & \ddots & \vdots \\ Bel(A_{i1}) & Bel(A_{i2}) & \cdots & Bel(A_{ij}) & \cdots & Bel(A_{in}) \\ \vdots & \vdots & \ddots & \vdots & \ddots & \\ Bel(A_{n1}) & Bel(A_{n2}) & \cdots & Bel(A_{nj}) & \cdots & Bel(A_{nn}) \end{bmatrix} \cdot \begin{Bmatrix} DP_1 \\ DP_2 \\ \dots \\ DP_j \\ \dots \\ DP_n \end{Bmatrix}$$

(4)

The design matrix elements are represented via belief functions $Bel(A_{ij})$. Their basic belief assignment (bba) (m) are defined by:

$Bel(A_{ij})$:

$$m(A_{ij}) = m\left(\left\{A_{ij} \mid A_{ij} \subseteq 2^{[\Theta(FR_i)\times\Theta(DP_j)]}\right\}\right) = P^{FR_i}_{\%DP_j} \cdot P^{DP_j}_{CL} \quad \text{(5a)}$$

$$m\big(\Theta(FR_i)\times\Theta(DP_j)\big) = 1 - m(A_{ij}) \quad \text{(5b)}$$

Where are:

$Bel(A_{ij}) = Bel(\{(FR_i)x(DP_j)\})$ – Belief function relating the functional requirement FR_i and the design parameter DP_j.

$m(A_{ij})$ – Basic belief assignment (m) for the focal element A_{ij} which is the subset of the frame of discernment $\Theta(FR_i)x\Theta(DP_j)$ defining the functional relationship between FR_i and DP_j.

$2^{\Theta(FRi)x\Theta(DPj)}$ – Power set (the set of all subsets) of the frame of discernment $\Theta(FR_i)x\Theta(DP_j)$

$P^{FR_i}_{\%DP_j}$ – Percentage participation of design parameters DP_j in the total variation of the functional requirement FR_i.

$P^{(FR_i \times DP_j)}_{CL}$ – Level of confidence, or probability of the assertion that the design parameter DP_j participates with $P^{FR_i}_{\%DP_j}$ in the variation of the functional requirement FR_i.

To substantiate the above we use the

experimental data of the elastomeric connector design from [Byrne and Taguchi (1987)] and give the method to describe the elements of the design matrix A_{ij} by belief functions which are based on experimental data obtained via the Taguchi method. This enables integration of the axiomatic design theory, the belief function theory and the Taguchi method of robust design.

Example 1.

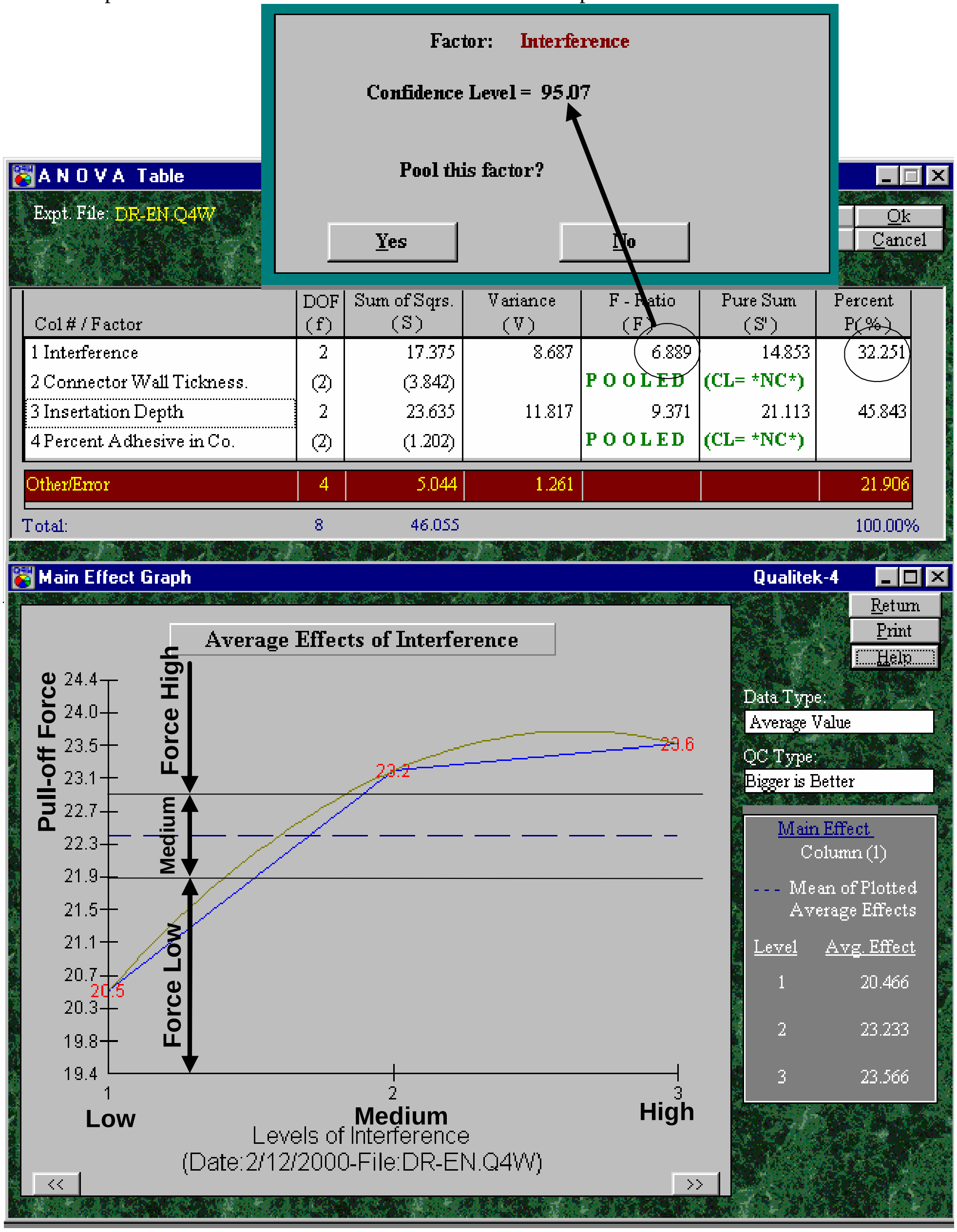

Figure 3. Taguchi experimental date in elastomeric connector design [Djapic (2000)]

An experiment was conducted to find a method to economically assemble an elastomeric connector to nylon tube that would deliver the requisite pull-off performance Fig. 3:

FR_2 – Maximize pull-off force
DP_2 – Interference connector
The design matrix element A_{22} (connect FR_2 and DP_2) is represented via belief function $Bel(A_{22})$. Their basic belief assignments (m) are defined:
$Bel(A_{22})$:

$$m(A_{22}) = m\left(\left\{\begin{matrix}(Force\_Low, Interference\_Low),\\ (Force\_High, Interference\_Medium),\\ (Force\_High, Interference\_High)\end{matrix}\right\}\right)$$
$$= P_{\%-Interferenc} \cdot P_{CL} = 0.32251 \cdot 0.9507 = 0.3095$$
(6a)

$$m(\Theta(FR_2)\times\Theta(DP_2)) = 1 - m(A_{22}) = 0.6905$$
(6.b)

An evidence resoning network for elestomeric connector example is presented on Figure 4.

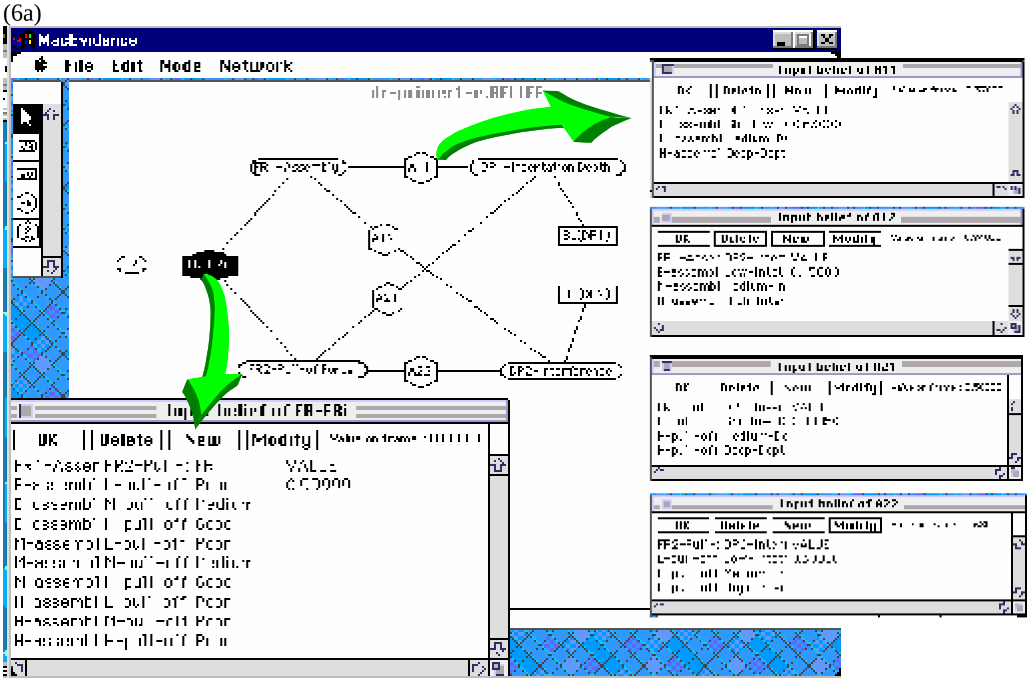

Figure 4. System Architecture as an Evidential Reasoning Network (example Elastomeric Connector) [Djapic (2000)]

Method for measuring customer satisfaction in uncertainty conditions

Method for measuring customer satisfaction in design process (Figure 5) based on using axiomatic design theory (first and second design axioms), Taguchi method robust design and belief functions theory.
It is based on next steps:

- Identification customer and its requirements
- Creation design solution using axiomatic design theory. Represent system architecture as an evidence network.
- Assessment design solution [*Bel* (*DPi*)] by a knowledge source (my by a designer or design teams) or by two knowledge source (my by two independent designer or two independent design teams)
- Evaluation evidence network. After evaluating the network, basic belief assignment $m(\{A\})$ is obtained which belong to the belief function of the basic functional requirement *FR* which represented base customer requirement.

The second design axiom (**information** axiom) refers to the selection of an optimal design solution from the set of solutions satisfying the first design axiom. The best solution among all possible alternatives is the solution carrying the least quantity of information, i.e., with the highest probability that design parameters will satisfy functional requirement(s) or customer requirement.

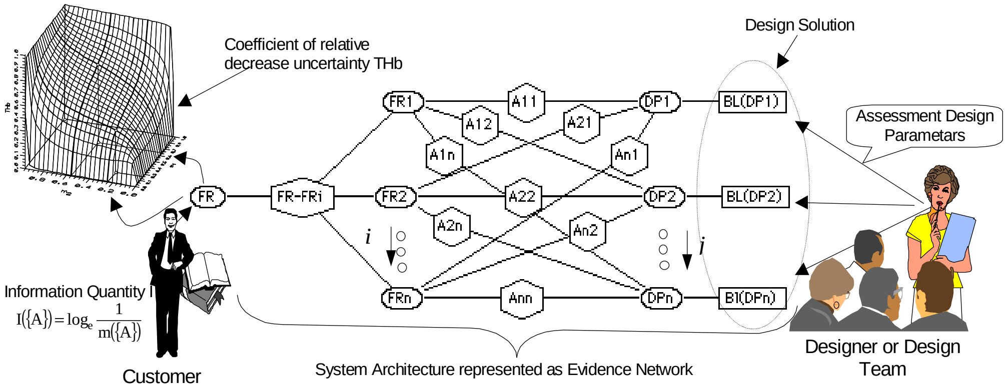

Figure 5 Method for measuring customer satisfaction in design process

Equation (Eq. 7) defines the information quantity when a particular functional requirement is satisfied expressed by belief functions:

$$I(\{A\}) = \log_e \frac{1}{m(\{A\})} \qquad (7)$$

Where:

Bel(*FR*)- Belief function of the basic customer functional requirement used to select the design solution.

m({*A*})- Basic belief assignment (*m*) for subset A of the frame of discernment for the basic customer functional requirement Θ(*FR*).

{*A*} - Subset of the frame of discernment Θ(*FR*) according to which the design solution is selected.

Example 2.

After evaluating the evidence network in the example of the elastomeric connector, the belief function for the basic customer functional requirement *Bel*(*FR*) [Djapic (2000)] is:

Bel(*FR*):
m({*Good_solution*})=0.41507
m({*Good_solution, Poor_solution* })=0.19438
m({Θ(*FR*)})=0.39055

When selecting the design solution for the elastomeric connector, the best solution is selected, i.e., the one which has the greatest basic belief assignment (*m*) for the {*Good_solution*} subset. This is the solution having the least quantity of information. Quantity of information *I* (Eq. 7) obtained after the { *Good_solution*} subset is realized is:

$$I(\{Good\_solution\}) = \log_e \frac{1}{m(\{Good\_solution\})}$$

$$= \log_e \frac{1}{0.41507} = 0.8793$$

(8)

One of the key features of the modern approach to products and processes design is teamwork. Project solution is evaluated, assessed by several project team members, by several organization departments, by different information and knowledge sources.

For the assessment and selection of design solutions under these circumstances, the coefficient of relative decrease of uncertainty can be used when the evidence or knowledge on the project solution coming from different sources is combined [Djapic and Milacic (1995)].

Coefficient of the relative decrease of uncertainty THb is a monotonously decreasing, dimensionless function. Its values are

represented by surface in Fig 1.
Using this coefficient and evidence network in selection design solution is shown on Fig. 6.

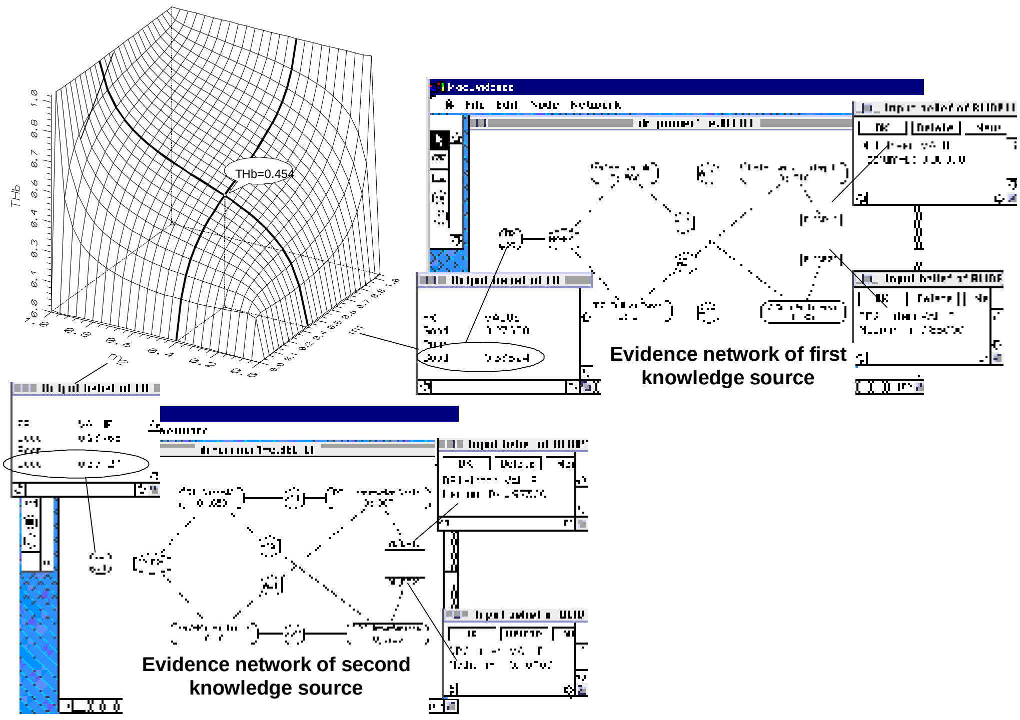

Figure 6. Using coefficient of decrease uncertainty and evidence network in selection design solution

6. CONCLUSION

In this paper we describes a method for measuring customer satisfaction in design process. It used information quantity measure for base customer requirement, which is expressed by belief functions. In situation when design solution is evaluated by two knowledge source we suggested using coefficient of relative decrease of uncertainty THb. This method enables integrated use of the axiomatic approach to designing, and the Taguchi method of robust design. This approach implies the modeling of the development process as an evidence reasoning network based on uncertain evidence described via belief functions.

REFERENCES:

[1] Byrne, D. M., Taguchi, S., 1987, The Taguchi Approach to Parameter Design, Quality Progress, December 1987, pp. 19-26.

[2] Djapic, M., 2000, Development a system for product / process design controlling with total quality paradigm, Ph.D. Thesis Mechanical Engineering Faculty, Belgrade.

[3] Djapic, M., Milacic, V., 1995, Using Uncertain Evidence in the Design Process, Second International Workshop on Learning in Intelligent Manufacturing Systems, Budapest, 19.-21. April 1995, pp. (1-23).

[4] Djapic, M., Milacic, V., 2000, New hybrid paradigm for product / manufacturing conceptual design based on theory of belief functions, The Third World Congress on Intelligent Manufacturing Processes & Systems, Cambridge, MA – June 28-30, 2000.
[5] Hintersteiner, J., Friedman G., 1999, System Architecture Template, Massachusetts Institute of Technology, Cambridge, 1999.
[6] Shafer, G., 1976, *A Mathematical Theory of Evidence*, Princeton University Press.
[7] Shenoy, P., 1989, A Valuation-Based Language for Expert Systems, Int. J. of Approximate Reasoning, Vol. 3, pp. 383-411.
[8] Shenoy, P., 1998, Reasoning with Dempster-Shafer Belief Function, MS&T Seminar, School of Business, University of Kansas.
[9] Suh N.P., 1990, The *Principles of Design*, New York: Oxford University Press, 1990. ISBN 0-19-504345-6.
[10] Suh, N., 1995, Design-in of Quality Trough Axiomatic Design, IEEE Transactions on Reliability, Vol. 44, No. 2, pp. (256-264).
[11] Tate, D., 1999, A Roadmap for Decomposition: Activities, Theories, and Tools for System Design, Ph D Thesis, Massachusetts Institute of Technology, 1999.
[12] Xu, H., Smets, P., 1995, Some Strategies for Explanations in Evidential Reasoning, IEEE Trans. On Systems Man and Cybernetics.

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