SELECTION OF NON-CONVENTIONAL MACHINING SYSTEMS BASED ON THE AXIOMATIC DESIGN THEORY

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ABSTRACT:

The best non-conventional machining (NCM) process for any specific application depends on several factors and constraints, including removal rate, accuracy, surface roughness, surface damage depth, corner radius, and costs. The NCM user must evaluate all these factors and constraints to select the most appropriate system, but there are not methodologies to support a consistent selection. This paper uses published information where NCM systems are compared to allow comprehensive analysis of application requirements versus process capabilities. The authors use Axiomatic Design theory, specifically the information axiom as a criterion to select the most appropriate NCM system. The procedure allows considering all the system factors to appraise the more or less probability of obtaining the specified functional requirements with each system.

KEYWORDS: Non-conventional Machining, Axiomatic Design, Engineering Decision-making

1. INTRODUCTION

At the present time, several non-conventional machining (NCM) systems are available, and the best one for each specific application depends on several factors, including material removal rate, accuracy, environmental operating characteristics, material properties, cost, and the existing constraints.

Therefore, the NCM user must assess all these factors to select the most appropriate system. However, there is a lack of sound methodologies to consistently support the above-mentioned selection.

This paper brings to play the available information about NCM systems to assess the application requirements versus the process capabilities, and Axiomatic Design (AD) is used to select the best NCM system for specific applications.

A procedure based on AD's Information Axiom is proposed, allowing for the inclusion of an arbitrary number of factors to appraise the likelihood of attaining the specified functional requirements with each one of the candidate NCM systems.

The procedure has remarkable differences regarding to the traditional decision matrix methods, in that it does not use weighing factors, and makes a clear distinction between requirements and constraints.

The usual way to set up an overall ranking procedure is to use "weighing functions", and the following weighing function gives the overall capability of each one of the candidate NCM systems:

$$C_S\left(c_{S1},..,c_{Sn}\right)=\sum_{i=1}^{n} w_i \frac{c_{Si}}{F_i}, \qquad (1)$$

where c_{Si} is the *i*-th specific capability of the system, F_i a scale factor, and w_i the weighing factor, so that

$$w_i > 0, \sum_{i=1}^{n} w_i = 1. \qquad (2)$$

Notice that the weighing factors are always subjective, for they express someone's belief on the relative importance of the considered criteria. In addition, it is worth to stress that weighing functions do not flag the solutions not complying with the selection criteria. At last, the effect of the weighing factors is to couple the otherwise independent evaluation criteria.

In this paper, we argue that a good means to overtake the above-mentioned difficulties is to use AD’s information axiom, provided that the functional requirements of each NCM system can be attained in an independent mode, as per AD’s Independence Axiom.

2. AXIOMATIC DESIGN

Axiomatic Design was developed in the late 1970s to be used as a systematic model for engineering education and practice. Its underlying hypothesis is that there exist certain fundamental principles that govern good design practice, and its key components are design domains, axioms, hierarchies and zigzagging [1, 2].

AD provides a general framework to assist in the decision making of any design process. Moreover, AD offers a means to show in detail and to assess the interplay between the design goals and the tentative solutions at any point in the design process.

AD key components are *design domains*, *axioms*, *hierarchies* and *zigzagging*.

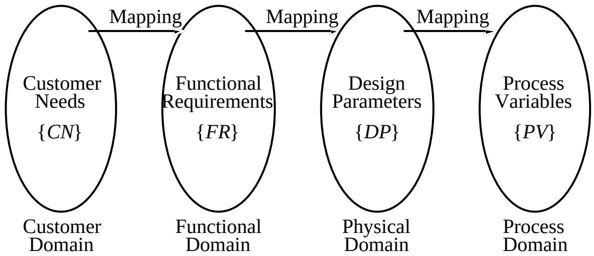

Fig. 1. The design process as a mapping [2]

According to AD, the design outcomes belong to one of four domains: the customer domain, the conceptual domain, the physical domain and the process domain (Fig. 1).

The design process begins in the customer domain with the settlement of the customer needs (CNs), i.e. the features that the customers are looking for in a technical system, being it a product, a process, or any other tangible or intangible system.

Mapping between the customer and the conceptual domains — a process that is currently known as “conceptual design” — is used to find out the functional requirements (FRs) of the technical system.

Another mapping — the “product design” — allows for the translation of the FRs into design parameters (DPs), which are the set of properties that describe the design object in the physical domain.

At last, mapping from the physical domain to the process domain — the "process design” — leads to the process variables (PVs), which outline how the product is to be made.

Each one of the above-mentioned mappings is not unique, and may lead to either “good design solutions” or “poor design solutions”, depending on the way they are performed.

In mathematical terminology, those mappings are represented by design equations. For the product design, for instance, we have

$$\{FR\} = [A]\{DP\} \tag{1}$$

where the generic element of the design matrix, [*A*], is given by

$$A_{ij} = \frac{\partial FR_i}{\partial DP_j} \, . \tag{2}$$

Distinct sets of DPs (or design solutions) may be settled to fulfil any specific set of FRs (or design problem). Consequently, the main job of the designers is to generate several possible solutions for the design problem, and try to adopt the best one for further development. According to AD, good design solutions are those that comply with the design constraints and that conform to the Independence Axiom:

The Independence Axiom: Maintain the independence of the functional requirements. (Alternative statement: In an acceptable design, mapping between the FRs and the DPs is such that each FR can be satisfied without disturbing the accomplishment of the other FRs.)

The existing relationships between FRs and DPs are key issue in the assessment of design solutions. In what to the independence axiom concerns, there are three basic design types: *uncoupled*, *decoupled* and *coupled*. Square design matrices characterize these basic types.

Uncoupled designs are the best and their design matrices are diagonal. Decoupled designs have triangular design matrices. This matrix shape makes them acceptable for they can be handled as if they were decoupled, provided that their FRs are adjusted in the appropriate order. All the other shapes of design matrices correspond to coupled designs that should be avoided [1, 2]. Examples of uncloupled, decoupled and coupled designs can be found elsewhere [1, 2, 3].

For any design problem, one can probably find two or more alternative solutions that are acceptable in the light of the Independence Axiom. In this case, the Information Axiom provides a quantitative means for evaluating the relative merit of such diverse options, in terms of the probability of achieving the design goals.

The Information Axiom: Minimise the information content of the design. (Alternative statement: From a set of designs that satisfy the same FRs and conform to the Independence Axiom, the best is the one with the minimum information content.)

For the simple case of a design with just one FR and one DP, the probability to attain the FR is given by:

$$p = \frac{(\text{area of the common range})}{(\text{area of the system range})}, \qquad (3)$$

where the area of the system range is computed from the FR's probability density function, and the area of the common range is the fraction of the above-mentioned area that is located inside the design range limits (see Fig. 2).

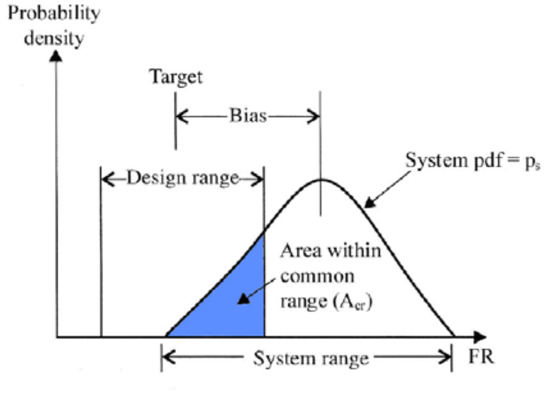

Fig. 2. The probability of success in a one-FR/one-DP design [2]

For this case, the information content is defined as:

$$I = \log_x \frac{1}{p} = -\log p\,, \qquad (4)$$

Usually, logarithms of base 2 are used, case of which the information unit is the *bit.*

For an uncoupled design with *n* FRs, the total information content, I_t, can be computed through

$$I_t = \sum_{i=1}^{n} -\log_2 p_i = \sum_{i=1}^{n} I_i \qquad (5)$$

where p_i is the probability of FR_i being satisfied by DP_i. Examples can be found in the references [1, 2, 4].

According to Axiomatic Design, the design of compound objects is to be developed in a top-to-bottom manner, beginning at the *system level* and progressing through levels of more detail, until a point that is enough to clearly describe the entire design object.

A unique procedure is used to achieve the design object synthesis, for it is quite different to analyse an already existing entity or to synthesise an object that still does not exist. This procedure is named *zigzag decomposition*, and its outcome can be depicted by a *tree-model* in each one of the four design domains. Some examples about the zigzag decomposition can be found in the references [1, 2, 5].

3. COMPUTING THE INFORMATION CONTENT

Let us suppose that one needs to select a NCM system for some specific applications on a basis of distinct criteria that can be considered independent.

The eligible NCM systems are the following:

- abrasive jet machining (AJM);
- chemical machining (CHM);
- electro beam machining (EBM);
- electro chemical machining (ECM);
- electro discharge machining (EDM);
- laser beam machining (LBM);
- ultrasonic machining (USM);

and the criteria to be used in the NCM selection are:

- material removal rate (MRR);
- accuracy (Acc);
- surface roughness (Ra);
- damage depth (DD);
- corner radii (CR);
- capital cost (CC);
- tooling & fixtures cost (T&F);
- power requirement (PR);
- tool consumption (TC).

Data about NCM systems capabilities can be found in several different publications, and we have adapted the data used in this paper from well-known sources [6, 7] (see Table 1). Notice that some of the capabilities are expressed using physical units, and some others in non-dimensional relative scales of different spans.

Table 1. Capabilities of the Different Systems

		USM	AJM	ECM	CHM	EDM	EBM	LBM
MRR (mm^3/min)		328	17	16383	17	817	1,7	0,12
ACC (0-10 rel. scale)		10	1	1	1	9	5	5
Ra (μm)	**min**	0,3	0,2	0,1	0,5	0,3	0,5	0,5
	max	0,5	1,5	2,5	2,5	38,1	2,5	2,3
DD (0-10 rel. scale)		9	10	10	10	5	1	5
CR (0-10 rel. scale)		10	10	10	1	10	9	9
CC (0-5 rel. scale)		2	1	5	3	3	4	3
T&F (0-5 rel. scale)		2	2	3	2	4	2	2
PR (0-5 rel. scale)		2	2	3	4	2	2	1
TC (0-5 rel. scale)		3	2	1	1	4	1	1

Table 2. System Ranges for the Different NCM Systems

		USM	AJM	ECM	CHM	EDM	EBM	LBM
MRR	**min**	0	0	0	0	0	0	0
	max	328	17	16383	17	817	1,7	0,12
ACC	**min**	0	0	0	0	0	0	0
	max	10	1	1	1	9	5	5
Ra	**min**	0,3	0,2	0,1	0,5	0,3	0,5	0,5
	max	0,5	1,5	2,5	2,5	38,1	2,5	2,3
DD	**min**	0	0	0	0	0	0	0
	max	9	10	10	10	5	1	5
CR	**min**	0	0	0	0	0	0	0
	max	10	10	10	1	10	9	9
CC	**min**	1,5	0,5	4,5	2,5	2,5	3,5	2,5
	max	2,5	1,5	5,0	3,5	3,5	4,5	3,5
T&F	**min**	1,5	1,5	2,5	1,5	3,5	1,5	1,5
	max	2,5	2,5	3,5	2,5	4,5	2,5	2,5
PR	**min**	1,5	1,5	2,5	3,5	1,5	1,5	0,5
	max	2,5	2,5	3,5	4,5	2,5	2,5	1,5
TC	**min**	2,5	1,5	0,5	0,5	3,5	0,5	0,5
	max	3,5	2,5	1,5	1,5	4,5	1,5	1,5

The expression “system capability” states the best performance of a system according to a definite evaluation criterion. However, AD’s Information Axiom claims for performance ranges, and not for best performance values. Therefore, we have settled Table 2 containing our interpretation of the system capabilities in terms of system ranges.

Along with this, one has to find out the shape of the probability density functions (pdf) that should be used for the system, as shown in the previous section. Data about NCM pdfs is not currently available. However, there is no reason to consider that some particular values of any of the system ranges are most likely to occur. Therefore, uniform pdfs are used in our study.

Next, one has to describe what is expected from the selected NCM system, that is, how the design ranges should be defined. In fact, Equations (3) and (4) clearly show that the information content of any NCM system depends not only on the capabilities of the system, but also on what we are expecting from it.

On this matter, we have defined four different scenarios.

Scenario A corresponds to average performance goals.

Scenario B is based on scenario A, but high accuracy, very smooth surfaces are required, and the incurred costs are not crucial.

Scenario C is also based on scenario A, but material removal rate is of paramount importance, as well as high accuracy and surface smoothness, and costs are not vital. This situation corresponds to the needs of high production rates.

At last, scenario D is also a modification of scenario A. In this case, sharp details and low damage depth are required at medium cost, and material removal rate is not important, which is a typical situation in the manufacturing of intricate components.

Table 3 characterizes the design ranges for the four above-described scenarios.

Table 3. Design Ranges for the Different Scenarios

		Scenario A	**Scenario B**	**Scenario C**	**Scenario D**
MRR	**min**	14,2	14,2	328,3	0,0
	max	19,2	19,2	16383,3	16383,3
ACC	**min**	3,5	7,0	0,0	0,0
	max	6,5	10,0	3,0	3,0
Ra	**min**	0,7	0,1	2,1	0,7
	max	2,1	0,7	38,1	2,1
DD	**min**	3,5	3,5	3,5	7,0
	max	6,5	6,5	6,5	10,0
CR	**min**	3,5	3,5	3,5	7,0
	max	6,5	6,5	6,5	10,0
CC	**min**	0,0	0,0	0,0	0,0
	max	2,5	5,0	5,0	2,5
T&F	**min**	0,0	0,0	0,0	0,0
	max	2,5	5,0	5,0	2,5
PR	**min**	0,0	0,0	0,0	0,0
	max	2,5	5,0	5,0	2,5
TC	**min**	0,0	0,0	0,0	0,0
	max	2,5	5,0	5,0	2,5

Table 4. Information Content (bit)

	Scenario A	**Scenario B**	**Scenario C**	**Scenario D**
USM	∞	11,1	∞	∞
AJM	∞	∞	∞	4,2
ECM	∞	∞	6,1	∞
CHM	∞	∞	∞	∞
EDM	∞	19,6	5,9	∞
EBM	∞	∞	∞	∞
LBM	∞	∞	∞	∞

Table 5. Systems Ranking

	Scenario A	**Scenario B**	**Scenario C**	**Scenario D**
USM	n/a	1st	n/a	n/a
AJM	n/a	n/a	n/a	1st
ECM	n/a	n/a	2nd	n/a
CHM	n/a	n/a	n/a	n/a
EDM	n/a	2nd	1st	n/a
EBM	n/a	n/a	n/a	n/a
LBM	n/a	n/a	n/a	n/a

Equations (3), (4) and (5) were used to compute the information content of each proposed solution for every one of the four considered scenarios, and the results are presented in Table 4.

4. DISCUSSION

Table 4 above depicts the total information content of all the analyzed NCM systems when they are used in the four considered scenarios.

As one can see, there is a considerable a number of situations where the information content equates to the infinity. These situations correspond to a zero probability of achieving at least one of the proposed performance goals.

The table clearly shows how powerful the AD-based selection criterion is: only four NCM systems (out of the seven) are appropriate for three (out of the four) operating scenarios. In addition, no one of the considered systems meets all the goals of scenario A.

Table 4 allows for setting up a ranking of the suitable systems for each case study based on the information content: the less information content, the better. Such ranking is presented in Table 5.

5. CONCLUSION

An Axiomatic Design based procedure to select NCM systems for any specific operating scenario was proposed in the present paper.

The focal point of the procedure is the quantitative assessment of the information content of the candidate systems, taking in account the operating goals to accomplish.

In order to achieve this, one has to precisely define both the system and the design ranges. The system probability density functions must be considered as well.

The method represents a remarkable improvement over the traditional multicriteria analysis method that was presented at the introduction, since it contributes for the understanding of the nature of the problem under analysis.

As for the deployed scenarios, it was made clear that the proposed method does not make use of subjective considerations, such as weighting factors.

It is worth to note, however, that the method is difficult to use without previous training.

Notwithstanding the difficulties, the AD-based procedure allows for easily get rid of the systems not complying with any one of the selection criteria, and to set up a ranking of the suitable systems.

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