MECHANICS AND MECHANICAL ENGINEERING
International Journal
Vol. 2 No. 1 1998

FROM DESIGN PRINCIPLES TO INTEGRETED COMPUTER AIDED DESIGN SYSTEMS

Jerzy Wróbel
Warsaw University of Technology
Institute of Machine Design Fundamentals
Narbutta 84, 02-524 Warszawa, Poland
Tel. (+48 22) 660-82-86, E-mail jerzy.wrobel@simr.pw.edu.pl

Abstract

In the paper the selected problems of the theory of machine design, formulated by prof. Zbigniew Osiński, are presented. The important elements of this theory are design principles. General and particular design principles are formulated also in mathematical way. The second general design principle is formulated in mathematical way as a problem of optimisation. In the paper also problems of multi-objective optimisation and decomposition of optimisation problems are considered as a particular problems of optimisation. Design principles are becoming the key to integrated CAD systems. The idea of such CAD systems is presented. Problems of safety in machine design are also discussed as an example of design principle and integrated CAD system. The data bases are proposed to support safety problems in design process.

1. Introduction

One of the more important, if not the most, trends in machine design is the appearance of computer tools (CAD). It is related directly to development of computer hardware and software as well. First attempts of implementation of CAD techniques go back to 1970s.

CAD systems become much more profitable when coupled with CAM systems (Computer Aided Manufacturing). The coupled

CAD/CAM system definitively shortens the time passing between the design and manufacturing process. CAD/CAM systems enable faster, cheaper and easier adjustment to the requirements of new constructions, implementation of corrections during manufacturing, small lot production, and manufacturing according to individual demands of a client.

The important development trend is a tendency to integrate all engineering works related to design, manufacturing, planning and managing in one effective system – Computer Integrated Manufacturing (CIM).

2. Design principles and mathematical model of a structure

Prof. Zbigniew Osiński formulates two general principles of design [5, 7]:

I principle:
A designed machine should satisfy all fundamental conditions ensuing from detailed rules (particular design principles) to the equal or higher extent from that assumed.

II principle:
A designed machine should be optimal (with respect to one or more objectives) in given conditions with respect to assumed criteria of optimisation.

Any design which follows the first principle is a good design. Usually, there exist a set of good designs (solutions). The designs satisfying the second principle are optimal (or polyoptimal) with respect to the assumed criteria of optimisation. Obviously, an optimal solution is a good solution.

From principles of design formulated as in the above one can draw essential conclusions. At first, there exist many good solutions, sometimes an infinite number of them. It is to be emphasised that the meaning of good solution is relative. It can be truly good or bad depending on definition of conditions imposed on the construction. These conditions are adjusted to the requirements to be fulfilled by the production plant.

Second remark refers to the necessity of being not satisfied by obtaining a good solution but permanent search of the best (optimal) solution. This is forced by optimisation criteria.

As it will be proven, such a formulation of the design principles can be expressed in a mathematical form.

The conditions imposed on a project determine particular design principles. The number of these principles does not have to be precisely defined, the set of them can be extended at every moment, if needed. But the fundamental principles that always have to be taken into account are related to functionality, reliability, durability, efficiency, lightness, cheapness and easy access to materials, simplicity of operating, ergonomy, ecology, conformability to the accepted regulations.

Except the above-mentioned fundamental principles there can also appear, in certain conditions, other requirements such as aesthetics, corrosion resistance, high- or low-temperature resistance, etc.

A formulation of a particular design principle is similar to a formulation of the fundamental principle. For example the functionality principle can be formulated as follows:

The designed machine should fulfil the functionality condition to the equal or higher extent from that assumed.

Each designed structure can be described uniquely by all structural parameters (geometric, material, dynamic). If we are able to represent each feature of designed structure by a single number or a set of numbers then we are able to describe the entire structure uniquely by the set of N numbers.

The structure can be regarded as a point x in the N-dimensional Euclidean space:

$$x = (x_1,\ldots,x_N) \qquad x \in R^N \tag{1}$$

The coordinates x_1, x_N can be separated into a group of the imposed parameters and a group of the coordinates to be fitted in the course of the design process. The latter group represent the so-called set of decision variables. Thus the structure can be described by n decision variables and P parameters:

$$x = \underbrace{x_1,\ldots,x_n}_{\substack{\text{decision}\\ \text{variables}}} \;,\quad \underbrace{x_{n+1},\ldots,x_N}_{\substack{\text{parameters}\\ N-n=P}} \tag{2}$$

Accuracy of calculations and quality of the obtained results depend on the assumed level of minuteness of detail. The designer is allowed to assume only certain (limited) values of decision variables. This comes from structural limitations ensuing from physical relationships between decision variables:

$$\psi_j(x_1,\ldots,x_n) = 0 \quad (j = 1,\ldots,m) \tag{3}$$

or in the form of inequalities:

$$\varphi_j(x_1,\ldots,x_n) \geq 0 \quad (j = 1,\ldots,q) \tag{4}$$

The set of points in the n-dimensional Euclidean space satisfying the structural conditions (3) and (4) is called the *feasible set* (set of feasible solutions). By describing this set by Φ, and assuming that the set is non-empty $(\Phi \neq 0)$, we can write:

$$\Phi \subset R^n \tag{5}$$

The designed machine which satisfies the first principle of design has to belong to the feasible set Φ. Thus the mathematical description of the first principle of design has the following form:

$$x \in \Phi\,, \qquad \Phi \subset R^n \tag{6}$$

The second design principle says that from all the feasible solutions (in the set Φ) one should choose the optimal solution, i.e. that one for which the objective function assumes an extreme value (either minimum or maximum).

The objective function is a function of decision variables:

$$Q = Q(x_1,\ldots,x_n) \tag{7}$$

The point at which the objective function reaches its extremum will be called the optimal solution (optimal project): $x_{opt} = (x_{opt1}, \ldots, x_{opt\,n})$.

The second design principle can be thus formulated in the following form:

$$(x_{opt} \in \Phi):\ \{\forall x \in \Phi \quad Q(x) \geq Q(x_{opt})\} \tag{8}$$

For the objective function one chooses a function related to structural conditions, such as efficiency, lightness, functionality. Very often it is related to costs. It can be a more complex function as well, e.g. referring to strains of a certain element, resistive forces in bearings, etc. The objective function can be a combination of numerous conditions.

3. Multi-objective optimisation

It quite often happens that we cannot stop with assuming only a single optimisation criterion. We need to consider much more criteria. If so, then we call the optimisation a multi-objective optimisation [4, 5, 7].

A multi-objective optimisation is most often defined on the grounds of the so-called partial order relation representing the positive cone in the *m*-dimensional quality space:

$$(x_{mul} \in \Phi):\left\{\forall x \in \Phi \ \neg\, Q(x) \overset{c}{<} Q(x_{mul})\right\} \tag{9}$$

where $\overset{c}{<}$ is the minority relation according to the partial order defined by the positive cone. According to (9), the solution of the multi-objective optimisation is such a solution, from all the allowable solutions, for which it is impossible to find a better one in the sense of the partial order described by the positive cone. Generally, in the area of accessible states Φ_q there exists the set of multi-objective optimisation states, and in the allowable area Φ, there exists the corresponding set of multi-objective optimisation solutions.

In the course of a machine design we have to choose one solution from all the obtained and satisfying the multi-objective optimisation criteria. It is to be emphasised that the choice is always subjective. There are two groups of methods of solving problems of multi-objective optimisation being applied in machine design. In the first group one recognises the entire area of multi-objective optimisation solutions and determines the corresponding quality indices. Thus created set is then submitted to experts who decide according to their knowledge, experience, intuition or other criteria (not considered in the mathematical model) which variant is to be realised. In the second group we have the methods converting the multi-objective optimisation problem into a simple optimisation (or a series of optimisation problems) with the optimisation criterion Q^* derived from the former m partial criteria. As a result we obtain a single point (solution) from the area of the multi-objective optimisation solutions.

4. Decomposition of optimisation tasks

Solving, by only multi-objective optimisation methods (without decomposition) with the help of the present computer measures, a large, global problem in the field of machine design is extremely costly and difficult to be realised [4, 6]. Large tasks would force designers to make decision simultaneously toward the entire problem, which is very hard when there are many criteria. A natural approach seems to be decision making in stages. For this one needs to decompose the large problem by following its natural multi-level structure.

Looking at the entire task, from the point of view of the relations, connections between the systems, one can state that there exist the quantities the choice of which is related exclusively to the given system and does not affect other systems, and there exist the other quantities, which have to be set jointly for a series of the systems. In the optimisation nomenclature the first quantities are called the *local decision variables*, the second ones – *co-ordination decision variables*.

In the domain of decision variables one can distinguish two levels of variables, i.e. there appear: vector of the co-ordination decision variables $\mathbf{v}$ (of the higher level) and vector of the local decision variables $\mathbf{m}^i$ (of the lower level). Due to the fact that the initial problem is a multi-criterial one it needs rational resolving of contradictions by using multi-objective optimisation methods.

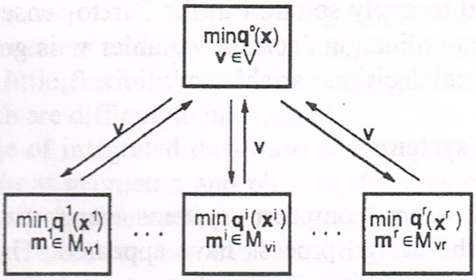

Fig. 1. Scheme of the large multi-objective optimisation task

The structure of a large optimisation problem makes it possible to solve the task in stages. The process of solving can be divided into two stages: resolving the contradictions within the local tasks, resolving the contradictions between the local tasks. The first stage can be realised on the lower level, the second stage on the lower one.

Engineering knowledge, in the field of machine design, concentrates mainly on directions related to designing machine elements and their parameters. A machine assembly is treated as a whole only in the case of certain classes of phenomena such as dynamics, wear, conductivity, etc. It is yet most often a one-aspect approach. This is why the knowledge of engineers is much more useful in the field of problems related to machine elements, or problems related to certain phenomena (local tasks of the lower level) than their capability to comprehend all the problems together with all relations between them (contradictions between the local tasks, the higher level). Consequently, we can accept the concept of differentiating the kinds of optimal conditions and the methods of solving the task from the lower and higher level. On the lower level it is possible and purposeful to apply preferential methods of multi-objective optimisation because of the above-mentioned reasons and because of the fact that the cost factor is very important since it decides about rationality of obtaining satisfactory results. It can happen that application of a given method produces the cost being unacceptable when compared to the quality of the obtained results. On the higher level, due to limited engineering experience, application of professional methods is more difficult. It is rather recommended to apply solution in the Pareto-sense, the more so as the number of the co-ordination decision variables **v** is generally less than the number of the local decision variables $\mathbf{m}^i$.

5. Integrated CAD systems

During last years computer systems supporting designers in different stages of the design process have appeared. These systems can help with geometric modelling, finite element analysis, simulation and optimisation with safety criteria. The industry to use their commercial versions in the design offices. Computer codes are available which can support the designer in nearly every field which is connected with the design process. Quite often one design office uses many different systems. This situation creates a number of new problems. Systems made in different software firms can have different data bases, processing and dialogue organisations. The data base is the heart of any CAD/CAM system feeding information to all the activities in the production process. The efficient structuring of the data is critical to both storage needs and execution speed. Different users (designers) should be able to access the same data base and pick out the data they need and don't be disturbed by the remaining data.

The data base should be discriminate between the logical data base (as a application programmer sees the data) and the physical data base (as the data actually is stored in the computer).

The most important feature of the design process is its complexity. The whole design process consists of a number of mutually interconnected subprocesses. The results of one subprocess can be input data of another one. According to that the use of many different computer systems on different stages of the design process needs their integration.

The integration can be done in one of the following ways [7, 8]:

a) via a system of interfaces which link different computer systems,

b) via an integrated data base, common for few systems,

c) via a two-level intelligent data base with a knowledge level.

The first approach is quite often used in practice. And it is very efficient in the case of little problems. Using it we should remember that it may be the beginning of a never finishing system of inter-system links. And every improvement causes with big changes in the software. This type of structure has little flexibility and is very dangerous if it achieves large dimensions which are difficult to understand.

The usage of integrated data base is very popular. The connection of information about geometric and physical features of the model in one data base is natural. On the market commercial data bases of this type are available. But with them one data base often dominates other.

The logical structure of integrated data bases is very difficult for fast and proper designing. Very often there are no flexible results, or "over flexible " results. We should remember that the integrated system is permanently developed and improved. Every change in the idea of storing information can cost a lot of work. Except for that this solution is very popular in practice.

The third idea seems to be especially interesting for a future applications.

The most important part of the integrated design environment is the data base. The data base should integrate all computer codes used in the design process. The structure of a data base should be open and allow to add new components. As mentioned before several solutions for the data base design are possible. The best solution seems to be a data base with knowledge level.

This kind of data base can be treated as an intelligent data base. Let's now consider a compulsory set of functions which should be offered by the data base.

The data base should allow to create connections between models which can be used by different computer systems. It should not allow to store redundant data and it should offer possibilities to reflect process aspects of design. It should be possible to archive older versions of some projects. It is very important to have the possibility of an intelligent searching in such archive or archive of standards. The archive should be equipped with functions which allow to store all development of some constructions but without redundant information.

The design process has its own dynamic structure. Some things should be done earlier, some later, some can be initiated after having done some others. A network can model it well. The design process of a new product is connected with many activities done by different people. The basic problem is how to optimally exploit the effort of single designers and how to coordinate their work globally. The data base should allow cooperation between different design sub-processes and store current state of them.

Intelligent solutions are needed because such a structure of a data base is not only a system for storing some information in some formal way. The data base should be equipped with different expert systems supporting nearly all activities.

6. Problems of safety in machine design

The data bases can comprise information about hitherto existing solutions, sets of design methods, sets of drawings of standard elements and machine assemblies, and information related to safety and health protection necessary to be taken into account in the design process and formulated in the state or international or European regulations and standards of the A, B and C type [1, 10, 11].

Inclusion of the problems related to safety to the design process together with using CAD systems enables harmonic matching the present requirements of the work safety and health protection with technological and economic conditions. Owing to the fact that these requirements should be considered during all stages of the design process it is important to make everybody involved in the project acquainted with them.

In order to implement up-to-date safety and health protection systems into design clearly and uniquely the possibility of using computer techniques has been considered [10, 11]. It has been concluded that such an approach should be based on: requirements of up-to-date regulations and standards, psychophysical characteristics of a human being.

In the design practice properties of a machine are well known from the point of view of technical parameters, but the knowledge of human characteristics is still poor. Hence, particularly in data bases, it is possible to store information about psychophysical characteristics of a human being such as:

– anthropometric dimensions of the human body and its parts, reach of the lower and upper limbs, motion capability of particular joints,

- biomechanical properties such as forces, moments developed by the human body during particular works and functions, especially during pulling, pushing, lifting, twisting, etc.,
- capability of the senses, especially of sight, hearing, touch from the point of view of receiving and discriminating information.

In computer data bases one can store the data related to work safety and comfort according to the above-mentioned characteristics and properties. The data can include:

- minimal distances preventing from crushing the human body, head, limbs, fingers, formulated in the standard PN-EN-349,
- dimensions of holes through which an operator reaches an element, e.g. for regulation,
- values of the resistive forces of steering elements for particular structural solutions.

In computer data bases one can finally store, and then analyse and apply in design, the data of the hitherto existing machines and devices similar to that being designed at the moment. The data is related to: basic technical characteristics of particular elements and assemblies, parameters of dangerous factors, harmful and burdensome operations ensuing from using these elements and assemblies, arisen consequences due to the above-mentioned factors (accidents, occupational diseases), opinions and remarks of the direct users on dangerous situations which only by a happy coincidence have not resulted in an accident, and on other dangers and difficulties occurring during operating similar machines, expectations of potential users.

Engineering data bases with all information necessary in design process are becoming more and more important tool in design office.

In conclusion we may say that design principles formulated by prof. Zbigniew Osiński are becoming the key to integrated CAD systems.

References

[1]. Bielecki Z., Wróbel J.: Data bases for design for safety of all-terrain cranes. Proceedings of ICED 95, V.Hubka (editor), Zurich, Heurista, 1995

[2]. Myrcha K., Pokojski J., Skotnicki S.: Symulacja komputerowa sytuacji zagrożenia przy obsłudze wybranych maszyn. Ergonomia, t.19, nr 2, 1996

[3]. Okulicz K., Wróbel J.: Zapis konstrukcji w systemach CAD. Przegląd Mechaniczny, 12, 1995

[4]. Z.Osiński, Pokojski J., Wróbel J.: Optimization of multilevel multicriteria machine design problems. Foundations of Control Engineering, Poznań, vol.8, 1983, 3
[5]. Osiński Z., Wróbel J.: Wybrane metody komputerowo wspomaganego konstruowania maszyn. PWN, Warszawa, 1988
[6]. Osiński Z., Wróbel J.: Towards decomposition of large optimization problems in machine dynamics. ZAMM (Z. angew. Math.Mech.), 74, 1994
[7]. Osiński Z., Wróbel J.: Teoria konstrukcji. PWN, Warszawa, 1995
[8]. Wróbel J., Pokojski J.: Intelligent data bases for the design of mobile cranes. Application of Artificial Intelligence in Structural Engineering, EPFL, Lausanne, Switzerland, 1994
[9]. Wróbel J.: Technika komputerowa dla mechaników. PWN, Warszawa, 1994
[10]. Wróbel J., Gierasimiuk J.: Computer Aided Design for Safety in Machinery. XIV World Congress an Occupational Safety and Health, Madrid, 1994
[11]. Wróbel J., Gierasimiuk J., Myrcha K.: Projektowanie wspomagane komputerowo, a kształtowanie bezpieczeństwa maszyn i urządzeń. Bezpieczeństwo Pracy, nr 7,8,9, 1992