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Engineering aspects of optimal design in automotive industry

by

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In the paper, after a brief historical overview to define today numerical simulation capabilities and to give some ideas of trends, the most important advantages and disadvantages of different available approaches in searching for optimal design solutions are discussed from Automotive Industry applications point of view with some considerations about particular aspects of most tipical problems.

1. Introduction

The Automotive Industry is currently undergoing a great evolution as regards design and design management which reflects the situation of the current calculating systems and the methodologies available in general.

In this way, new, specifically designed products are launched in as little time as possible in order to try and keep up with the competition, which now takes place on a world-wide scale.

This entails both "assimilation" and thus a need for a broader base of knowledge, personal training, and the optimization and transfer of methodologies, and "stimulation" of research towards new frontiers to tackle new problems as they arise.

The major concrete aims resulting from the needs are:

a) Reduction of the lead time of a new model.

b) Reduction of the overall costs of the model, not only those established at the time of purchase, but also subsequent costs associated with its entire life.

These objectives are pursued with "total quality" scientific and management systems and their achievement implies the search for optimal and robust solutions in design of components and processes.

As far as optimization methods and tools in particular are concerned, their impact in design procedures and in the technical office's organization is very relevant: it is not only an improvement of software and hardware tools, but it implies a new way of thinking.

In fact till now the designers were able to perform a verification analysis of its design solutions by the definition of the corresponding numerical models; now it becomes possible to get new design solutions better than the starting one automatically at all by the definition of a "design model". The corresponding jump of expertise and culture is very different and higher from the qualitative point of view respect to the past, when the designer gradually left the hand calculations and utilized the computers: at that time in fact the analysis was anyhow a verification analysis also if with more powerfull tools.

In this context, a lot of methods and tools are becoming available which are based on different approaches from the philosophical point of view and with a large variety of features: in particular two main groups can be evidenced concerning respectively the "sequential approach", for the direct search of optimal design solutions, and the "parameter design" procedures, based on statistical data analysis.

Besides another completely new field is being developed other than the computational one: Artificial Intelligence and expert system areas, which seems to be very promising and potentially suitable to improve the design optimization procedures.

The above different approaches may be integrated advantageously to reach the desired results with greater success: this is the most important thing to achieve and thus constitutes a challenge to be faced in the near future.

To do this, it is important to be fully aware of the current situation and to consider it from various viewpoints, and even more so to retrace the steps that have led to present-day technology and the design methods currently available to better understand future trends.

2. Historical Panorama

When examining the current situation in the light of the recent developments, 2 major trends may be recognized:

a) Various sectors of industry have acted as stimuli to the development of methodologies and calculating systems at different points in time. The motives behind the greater demand for research have been extremely varied and differentiated; the major determining factors were:

- The technical need for carrying out complex calculations essential to the manufacture of the products, togheter with the difficulty, or even impossibility, of carrying out experimental tests: this is the case for example of the aerospace, ship-building and civil engineering industries.
- The existence of strict regulations imposing specific calculations and studies to be carried out to ensure safety in high-risk installations : this is the case for example of nuclear power plants and chemical industries, and many other civil engineering projects.
- A need for improvement in the technology, cost and quality of the product, on a competitive market, together with a touch of "image", which imposes, and continues to impose, evolutions in design : this is the case of the mechanical industry in which the most advanced calculating methods have been applied more recently, considerable recours still being made, however, to the experimental approach.

This is easy to understand when one considers both the relative ease with which the various products may be designed and built, compared for example, with the civil engineering or aerospace industries, and the limited number of Regulations specifically defining the tasks of components and the design requirements to be met for the various operating conditions of the product.

b) The integration of scientific research in different sectors, in other words, multi-disciplinary knowledge, and the exchange of ideas and results, is, as it always has been, a determining factor in making great progress.

From this point of view, the progress and combined forces in particular in the fields of mathematics, physics, engineering and electronics have broadened our horizons, increasing the possibilities and methods of tackling problems.

If we consider the last tenths of years, we may state that during the early stages of the development, there was a shift from a myriad of calculating methods to a single method [13] of solving problems of phisycs (mechanics of solids, potential fields, fluids), the generalized finite element method, the application of which led to the replacement of the "calculations" by the "Model". This means that, instead of performing calculations using formulae or procedures with varying degrees of complexity, the numerical model of the problem, generally based on less simplified hypothesis, is constructed and then analyzed, obtaining a more complete range of information.

Later on, another great step forward was taken, with the shift away from the "numerical model" of a problem towards the "numerical simulation" of an event : these new horizons have been broadened very recently and impressive developments are in progress.

To associate these stages with the developments in computer science that brought them about, we may say that the shift from "problem-oriented formulae" to "numerical models" occurred as consequence of computers availability, and the second shift from "numerical models" to "numerical simulation" is occurring at the same time and as a result of the widespread use of supercomputers, with vector and parallel architecture.

If we try to better define what "numerical simulation" actually means, it is possible to identify 3 main areas of evolution:

a) The continous effort to place numerical models in a broader context, both in space and time, taking into consideration how the components and modelled structures interact with their operating environment.

   In this context, new kinds of analysis can be performed:

- Analysis not only of single components, but of whole systems (gear-box, engine, vehicle).
- Coupling of different models concerning for example continuum mechanics, fluids, thermal fields.
- Technological processes simulation (Sheet metalforming, forging, injection moulding).
- Experimental testing simulation (Crash).

b) Real time simulation of systems to optimize the design and better check the performances of control systems (suspensions, antiskid).

This is a quite recent area of research where high speed computer and efficient and reliable numerical models open new impressive possibilities.

c) Design Automation, by the development of methods and tools suitable to simulate the iterative process of designers to find optimal and robust solutions for their projects.

Looking at the above scenary, it is important to realize that the numerical simulation capabilities are the actual basis for a new approach to design and product development, which is known as "Simultaneous Engineering" or "Concurrent Engineering" methodology, characterized from a tendency to shift many activities of the production cycle to the design phase, so as to reduce the product's lead time.

In fact the possibility of simulating events and not simply analysing models paves the way for the gradual replacement of experimentation on real components with "numerical experimentation", thus enabling the following major advantages to be obtained:

- Components may be tested in their operating conditions without having to build them.
- It becomes simple and feasible to analyse many alternative solutions on the computer and then try to improve considerably, if not actually optimize, the components and systems already during the design phase, while the new product is still at a conceptual level.

Now a question arises : what is the new role of the "experimental approach" in Automotive Industry and what is its relation with "numerical simulation" capabilities?

In the Automotive Industry "experimental testing" was traditionally seen as a method of designing that involved both a long and costly process whereby the prototypes were tested on the workbench or on the road as early as possible, subsequently making modifications as the need arised.

It must be seen now no more as a design method, but as a strategically important method of testing and adjusting the models of analysis and simulation, thus contributing at this stage to an increase in the knowledge of the problems, and subsequently enabling the final solution to be tested after it has been optimized and stabilized.

3. Optimization and robustness approaches in design

In the past, and to a large extent even today, the designer's work, both when he carried out direct calculations and, more recently, when he used even quite sophisticated models, was based on the "testing" of solutions created and defined by him in some way.

The results of the test were then analyzed in the light of his experience and overall vision of the various problems: resistance, operational features, manufacturing processes, transportation of the manufactured products and so on.

In this way, the initial ideas were evaluated and the designs modified leading to new designs to be tried out and repeating this cycle until a final solution was obtained that proved satisfactory from all points of view, the optimum solution considering the various parameters involved and their relative level of priority: this is the "redesign" method which, in certain specific cases, for example steel constructions, had already been automatized in the past with special-purpose analysis programs.

Today, there seem to be greater possibilities for the immediate future of developing automation, with more efficient methods, and extending it to a greater number of applicational fields, with a view to obtaining a "better" product, an "optimum" answer to the design specifications required and a "stable" solution from the point of view of reliability and operational features.

There are many ways of proceeding in this direction, each one having its own advantages and disadvantages, as a result of their capacity to cover only some of the aspects of a problem : hence the need for integrating methodologies, using each methodology in its intrinsic context only, and not as "ideology" on which to base our way of tackling all the aspects of the problem.

The first line of development, which seems to be the natural continuation of the history outlined previously, is the optimization with deterministic models based on the sequential search for the "optimum" design [7,8,10].

The integration of major lines of research, the Finite Element Method, on the one hand, and Mathematical Programming methods on the other, is facilitating the creation of calculating programs that are able to search for the optimum solution for a structural design by defining a "verification model", which describes the object under study, and a "design model" associated with it : the latter comprises the variables that may be altered during the search, the optimization aims and the constraints to which the solution must be subjected.

The problem typically consists in finding a solution in which a component has the lowest weight possible or in which its shape ensures a reduction of stress concentration factors.

The search procedure begins with an initial attempt which may be quite different from the final solution and, after repeated tests, results' analyses and subsequent modifications, moves into the design space to determine the minimum/maximum of the objective function.

These methods are now in a position to help designers considerably in that they go beyond the concept of "verification analysis" towards an automatic search of improved solutions based on an initial one.

They have applicational limitations, however, which may be quite serious, particularly in the case of mechanical engineering projects, and which are linked mainly with the following aspects.

a) Work is necessarily carried out on an initial model which entails 2 levels of approximation compared with reality: idealization intrinsic to the concept of a model and numerical approximations, for example the choices made when defining the finite element mesh, whose accuracy level should be guaranteed by error valuation and iterative adaptive procedures application.

b) Some aspects of the problem that should be taken into consideration during the design phase are hardly ever dealt with in mathematical terms within the model due to the great difficulties encountered in their idealization: for example, the problems associated with the technological forming processes, assembly procedures, maintenance in operation, operational reliability with the passage of time and so on.

c) This automation of the choices between widely-differing alternatives entails creating higly complex verification and design models requiring a great deal of effort that are still today difficult to handle, so automation is limited mainly to finalizing a design for which many choices have already been made, using various criteria and tools.

d) Within this context, consideration is not so easy given to all that is not deterministic both as regards operating conditions, for example static and dynamic loads applied or materials behaviour, and operating modes, for example clearances and manufacturing tolerances.

To remove these limitations, research and development programmes are being conducted in various disciplines, following a tendency towards integration and can be identified in brief as follows:

a) Artificial Intelligence techniques [6], in particular expert systems, which are now adopted in many applicational areas and, for the future, neural networks on which research is being intensified, with the aim of:

- Taking into account aspects that are difficult to evaluate mathematically in the models, handling non numerical, as well as numerical, information and data.
- Improving the quality and reliability of the models by optimizing the meshes, making the numerical models correspond to the geometrical ones (CAD-FEM interfaces), and facilitating modelling choices through the creation of expert systems designed to provide specific information on the topic, etc ...
- Improving the accuracy with which the calculating results are evaluated and handling them in the repetitive optimization process.
- Controlling as a whole the design optimization and management process by coordinating the different "tools" used during the various analysis and decision-making phases.

b) Methods for the handling of numerical models which take into account the probabilities associated with the variables involved in the problem in which the strategy of iterative search is still sequential.

c) Parameter Design methods [3,9,11,12], of which the Taguchi methods is probably underservedly the most well-known, which are very popular particularly in Automotive Industry environment.

They are based on an extremely pragmatic approach to the problems and are aimed at finding, rather than the "optimum" design solution in the classical sense, the most stable as regards dispersion of the parameters characterizing and defining it from the estimated values, so as to ensure greater operational reliability during the product's life.

The origin of these methods lies in the field of Experimental Testing and Manufacturing : so their approach to the optimization problems is a "parallel approach"; instead of moving in the design space from one point to another in search of the minimum of objective function, numerous points are studied at the same time, in parallel, looking for the best solution by analysing all the calculated results and obtaining a knowledge about the whole design space which has been considered.

In this way it is also easier to include in the procedures the analysis of aleatory aspects of the problems, taking into account not only the systems response but also their variance: in this sense they are particularly valid for tackling and handling the problems and the objectives involved in improving the quality of products in Automotive Industry environment.

Besides the possibility of performing now "numerical simulations" instead of physical ones creates a great sinergy towards "Simultaneous Engineering" philosophy and allow to overcome limits which are intrinsic to parameter design methods due to great number of experiments necessary when there are too many design variables to be taken into account.

4. Applications

A fundamental step for the automation of design procedures in order to achieve optimal and robust design solution consists in being able to evaluate the reliability of models on which the iterative search is based and the accuracy of analysis results which are obtained: so a general procedure for meshes optimization like in fig.1 should be taken into account.

If we consider then the most important applications in Automotive Industry we may realize that only for some of them the development of methodologies and simulation capabilities of design solutions allow to face with problems of automation of optimal design both with sequential and parallel approaches.

In the case of Vehicle Dynamics System for example and in particular for suspensions the state of the art of numerical models performances is quite advanced, both for kinematic and structural analysis : so next step of looking for optimal design solution can start according to general design procedure shown in fig.2.

Also, where structural analysis is a fundamental step for a correct design of components, the search for optimal design solution can be faced with : in gear teeth stress analysis for example, 3D numerical models based particularly on p-FEM [1] or BEM formulations are well tested from results accuracy point of view and are very user friendly for design purposes (fig.3).

Instead in the case of engine systems, in which the optimization goals are so complex and conflicting each other and more sophisticated analysis [2,5] are required based on global models able to study structures, thermal fields, fluids and chemical reactions (fig.4), the optimization procedures are still very difficult to implement and generally only analyses related to local optimization sub-goals can be dealt with.

The analogous situation takes place in the case of technological processes optimization (fig.5), in which a great research effort must be still performed in developing efficient and reliable numerical simulation capabilities [4].

5. Conclusions

We can conclude the above scenary concerning engineering aspects of optimal design in Automotive Industry with the consideration that the greatest effort in research now and probably in the next future consists essentially in improving numerical simulations capabilities and in educating technical people in utilizing with better knowledge the most advanced tools for their own design purposes.

The research activity concerning the application of optimization and robustness methods in Automotive Industry is increasing, but for the moment it is at a pioneristic level: its own goals are focused in testing and evaluating several different approaches to automotive components and systems design to better understand related capabilities and how to utilize and integrate them.

References

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Figures

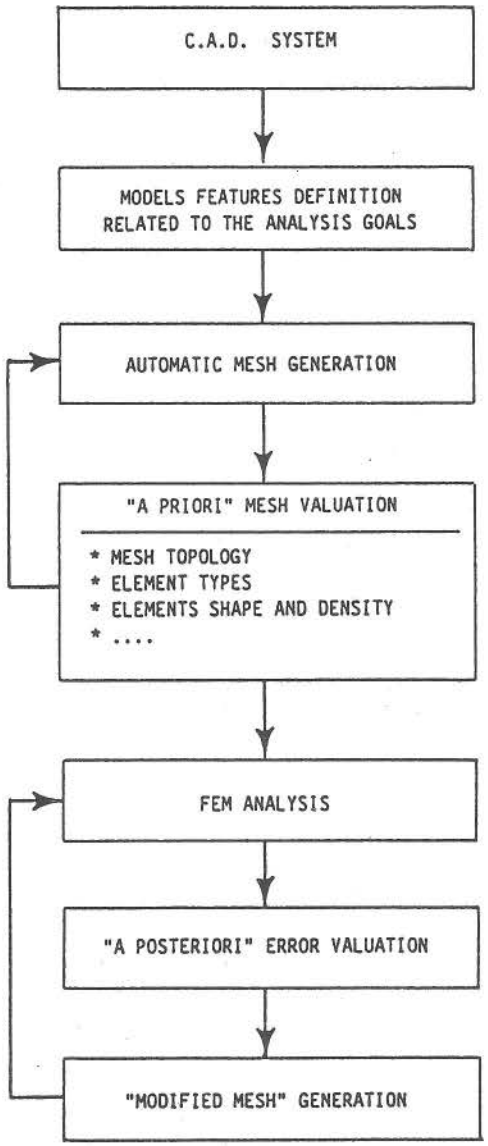
C.A.D. SYSTEM
MODELS FEATURES DEFINITION RELATED TO THE ANALYSIS GOALS
AUTOMATIC MESH GENERATION
"A PRIORI" MESH VALUATION
* MESH TOPOLOGY
* ELEMENT TYPES
* ELEMENTS SHAPE AND DENSITY
* ....
FEM ANALYSIS
"A POSTERIORI" ERROR VALUATION
"MODIFIED MESH" GENERATION

Fig. 1

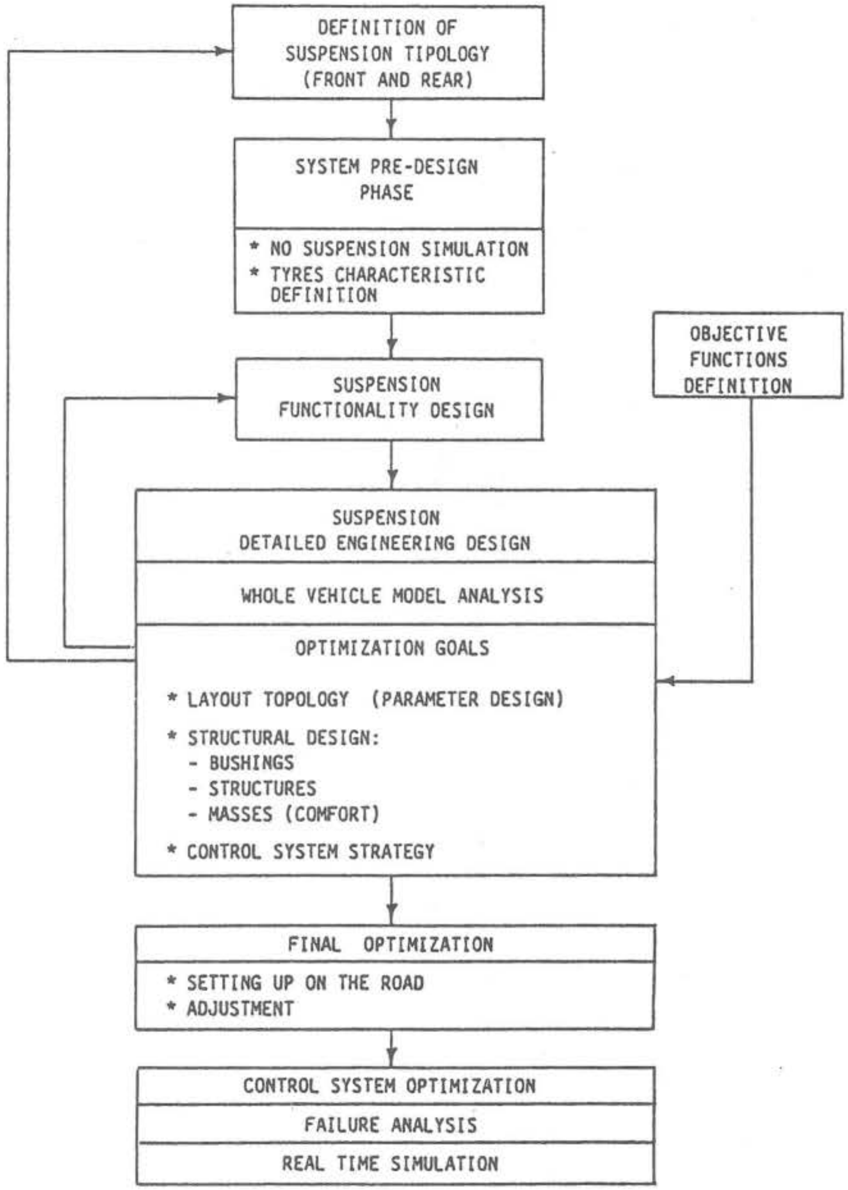
DEFINITION OF
SUSPENSION TIPOLOGY
(FRONT AND REAR)
SYSTEM PRE-DESIGN
PHASE
* NO SUSPENSION SIMULATION
* TYRES CHARACTERISTIC
DEFINITION
OBJECTIVE
FUNCTIONS
DEFINITION
SUSPENSION
FUNCTIONALITY DESIGN
SUSPENSION
DETAILED ENGINEERING DESIGN
WHOLE VEHICLE MODEL ANALYSIS
OPTIMIZATION GOALS
* LAYOUT TOPOLOGY (PARAMETER DESIGN)
* STRUCTURAL DESIGN:
- BUSHINGS
- STRUCTURES
- MASSES (COMFORT)
* CONTROL SYSTEM STRATEGY
FINAL OPTIMIZATION
* SETTING UP ON THE ROAD
* ADJUSTMENT
CONTROL SYSTEM OPTIMIZATION
FAILURE ANALYSIS
REAL TIME SIMULATION

Fig. 2

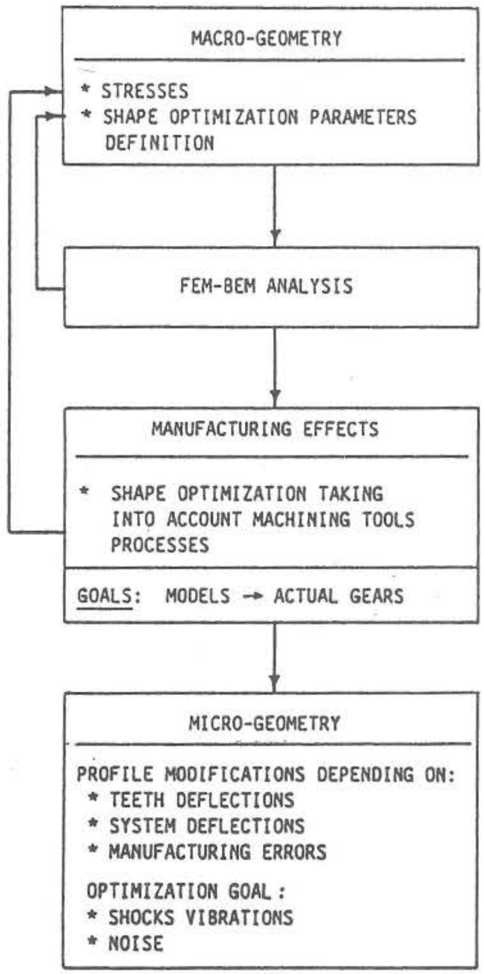
MACRO-GEOMETRY
* STRESSES
* SHAPE OPTIMIZATION PARAMETERS DEFINITION
FEM-BEM ANALYSIS
MANUFACTURING EFFECTS
* SHAPE OPTIMIZATION TAKING INTO ACCOUNT MACHINING TOOLS PROCESSES
GOALS: MODELS → ACTUAL GEARS
MICRO-GEOMETRY
PROFILE MODIFICATIONS DEPENDING ON:
* TEETH DEFLECTIONS
* SYSTEM DEFLECTIONS
* MANUFACTURING ERRORS
OPTIMIZATION GOAL :
* SHOCKS VIBRATIONS
* NOISE

Fig. 3

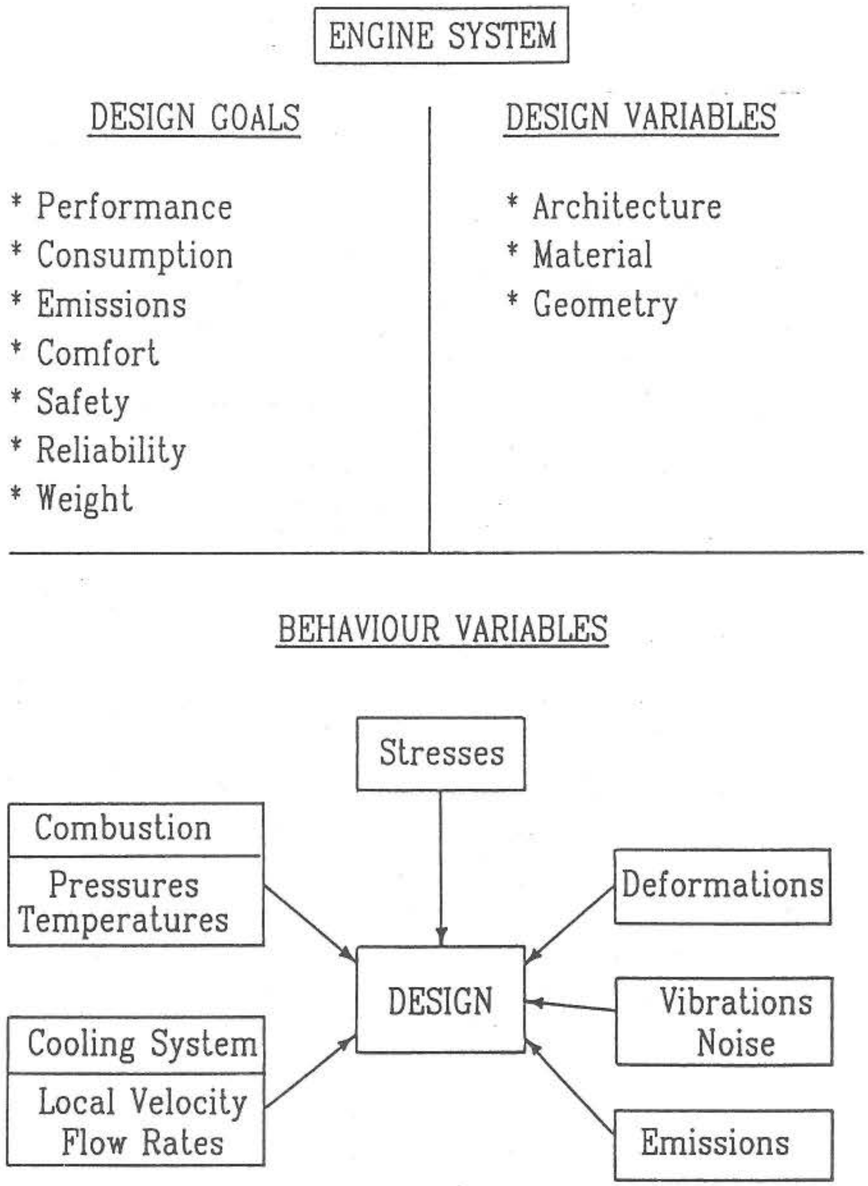
ENGINE SYSTEM
DESIGN GOALS
* Performance
* Consumption
* Emissions
* Comfort
* Safety
* Reliability
* Weight
DESIGN VARIABLES
* Architecture
* Material
* Geometry
BEHAVIOUR VARIABLES
Stresses
Combustion
Pressures
Temperatures
Cooling System
Local Velocity
Flow Rates
DESIGN
Deformations
Vibrations
Noise
Emissions

Fig. 4

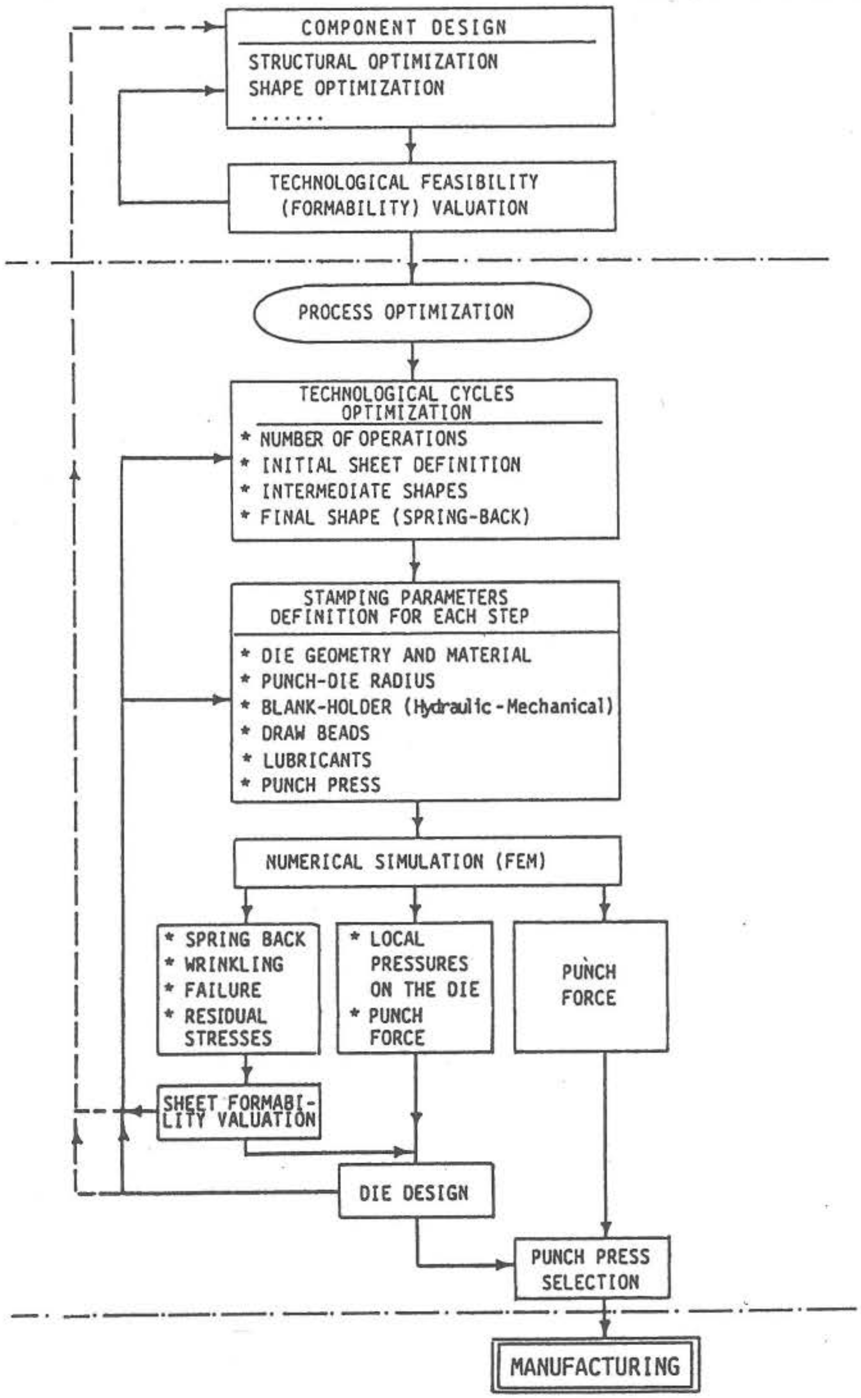
COMPONENT DESIGN
STRUCTURAL OPTIMIZATION
SHAPE OPTIMIZATION
....
TECHNOLOGICAL FEASIBILITY (FORMABILITY) VALUATION
PROCESS OPTIMIZATION
TECHNOLOGICAL CYCLES OPTIMIZATION
* NUMBER OF OPERATIONS
* INITIAL SHEET DEFINITION
* INTERMEDIATE SHAPES
* FINAL SHAPE (SPRING-BACK)
STAMPING PARAMETERS DEFINITION FOR EACH STEP
* DIE GEOMETRY AND MATERIAL
* PUNCH-DIE RADIUS
* BLANK-HOLDER (Hydraulic-Mechanical)
* DRAW BEADS
* LUBRICANTS
* PUNCH PRESS
NUMERICAL SIMULATION (FEM)
* SPRING BACK
* WRINKLING
* FAILURE
* RESIDUAL STRESSES
* LOCAL PRESSURES ON THE DIE
* PUNCH FORCE
PUNCH FORCE
SHEET FORMABILITY VALUATION
DIE DESIGN
PUNCH PRESS SELECTION
MANUFACTURING

Fig. 5