# ASPECTS OF INTEGRATED CAD/CAM FOR ADVANCED MANUFACTURING

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**Abstract: Integrated CAD/CAM or VPD (Virtual Product Design) is a concept that can optimize an organization's business edge, if properly implemented. It provides a unique process based approach and enables a seamless digital design-through-manufacture environment. The elements and concepts that make it possible are presented in the general context of CAD/CAM theory and then discussed in the particular context of a very popular CAD/CAM system: Pro/ENGINEER.**

## I. INTRODUCTION

The primary goal of engineering is to transform ideas into products that are reliable, safe and economical. The process of designing and introducing a product to manufacturing involves a sizable effort in various disciplines and a large amount of resources. This process of Product Development has benefited enormously from the introduction of Computer-Aided Design or CAD systems. Similarly, manufacturing has seen a watershed event with the introduction of numerically controlled (NC) and Computer Numerically Controlled (CNC) machine tools. They offer increased flexibility, superior accuracy and shorter production cycles not to mention the possibility of manufacturing hitherto impossible forms and shapes like sculptured surfaces. [1]

It has been recognized that the farther down in the product development cycle a change is introduced, the costlier it is to incorporate it into the design. [1] This gave rise to the concept of *Integrated CAD/CAM*. We strive to present the elements and concepts that make it possible, first in general theoretical terms and illustrate these with the help of a very popular CAD/CAM system: Pro/ENGINEER. In the process, we shall introduce the reader to the state-of-the-art in technology while not losing bearing with respect to practical concerns. While there is some literature in this field (e.g. [2]), a strong need is felt for literature in the area of integrated systems to illustrate the concepts and demonstrate workability in *practical* everyday design-through-manufacture situations. It is for this reason that while writing this paper we have taken the case of a Rear Cover of an electrical motor as an example.

## II. Pro/ENGINEER: FEATURES AND IMPORTANT CHARACTERISTICS

Pro/ENGINEER is one of the advanced systems available in the CAD/ CAE/ CAM/ PDM marketplace today. It enables multiple disciplines to contribute simultaneously to a single product model. Later in this paper we shall discuss some of the disciplines that are extensively involved.

The important characteristics that led to our choice of this particular system to present the concept of "Integrated CAD/CAM" are the following:

### A. Full Associativity:

The fact that all Pro/E solutions are associative implies that a change made anywhere in the development process can be propagated throughout the entire design, even updating the deliverables like drawings and NC data.

### B. Feature-based Modeling:

A very important requirement from the CAD system to support the development of an integrated approach is the possibility of building in more and more knowledge on the product design. Here product geometry is modeled with the use of cognitive features like holes, rounds and fillets etc. that apart from defining the form of the design, also contain knowledge of their environment and hence adapt predictably to this change. [3] The concept is illustrated later in the paper for Air Vents in the rear cover.

### C. Parametric Modeling:

In continuance of the above characteristic, with Parametric modeling it is possible to dictate *form, fit and function* by defining the model in terms of constraints or design parameters. The parameters *drive* the geometry and they can be modified to easily explore multiple design iterations. The parametric as well as the feature-based characteristics provide the designer with power and flexibility in incorporating the design intent in the product model. We shall illustrate this concept later in the paper. [3]

C. Data Management

Another important characteristic of a system amicable to Integrated development is one which allows multiple users to access the same database, even from different platforms and operating systems, while still retaining the integrity of the database, as well as control version updates. [4]

## III. ASPECTS OF INTEGRATED CAD/CAM

A. Product Design & Modeling

The concept of digitally creating a product model may be easily understood by thinking of it as modeling using "*Electronic Clay*". The importance of this stage will become evident as we proceed in our discussion of the downstream stages.

This stage essentially involves the geometric modeling of the part being designed, where the object data is represented as a mathematical model with the help of a commercially available software code. This code is commonly known as a CAD package, that could be an internal module of a more integrated software package or a standalone design application. In what we shall illustrate now, Pro/E offers the possibility of creating design models in an advanced Parametric-Feature based environment. It allows us to create complete virtual representations of the physical object being designed.

Before we proceed, it is important to discuss the concept of "*Parametric*" design. Any design that is being pursued is characterized by a set of design variables and constraints, mostly defined by the application function.

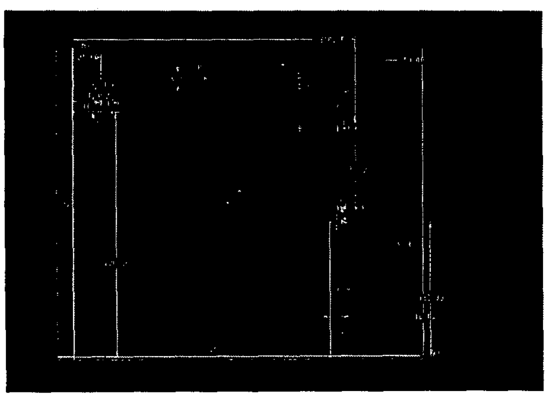

Figure 1. A dimensioned sketch

Multiple design solutions can be and are achieved by changing these variables, as the model quickly updates automatically reflecting the changes. Further, these changes are propagated to update other parts/assemblies/drawings that may be affected in the bigger picture of product design.

These design variables can be effectively limited and possibly reduced to an optimum minimum set, which can then be controlled by mathematical relations comprising of meaningful design requirements. In Figure 1, the section material thicknesses defined at various locations in the sketch are actually governed by parametric relations. These are shown below:

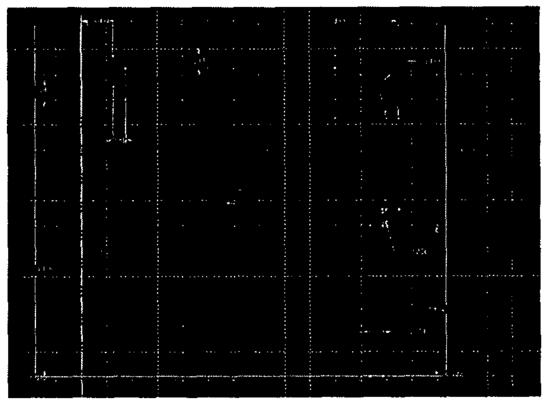

Figure 2: Sketch showing Data labels on dimensions

These relations allow us to change and update the solid model with a single change of the thickness parameter 'sd5'. Based on the value of this single parameter the value of all the rest 'sd6', 'sd7' and 'sd29' are automatically updated. The user cannot even accidentally change these parameters that draw their values from the basic parameter 'sd5'.

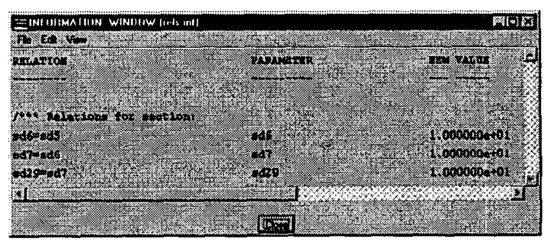


Figure 3: Material thickness dimension labels defined in Relations

This complete process of driving the physical shape of the part/assembly by the values of the basic set of the design variables is one of the methods of implementing *Parametric Design*. This however, is not the only way of introducing the *design intent* into the product model.

At the highest level, the intent can be captured right from the beginning of the modeling process. The most important being the choice of features and their types, that are used to model the form of the part. Later, more of the design intent may be introduced at the feature level by creating Parameters and Parametric relations such as the one illustrated above i.e. the section thickness. Even the dimensioning references create relationships between features and can be judiciously used to capture the design intent.

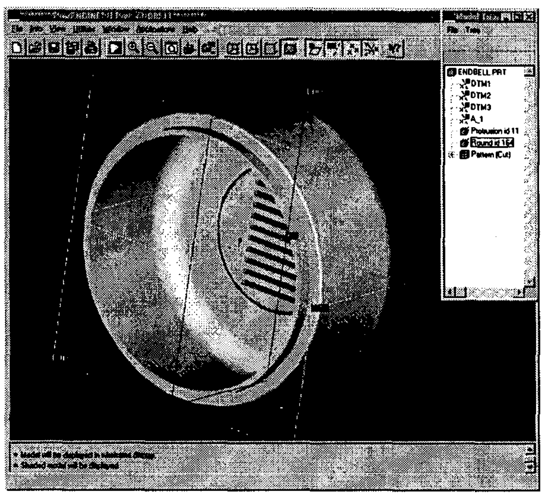

Figure 4: A completed Solid Model

The concept of *Feature based* modeling also plays an important role at this point. The fact that the Air Vents are provided to allow air passage through the end-bell is the design intent. These vents are modeled here as a pattern of features deriving their extents by association to the bounding surfaces i.e. the inside and outside faces of the end bell. This method constraining the vents allows the system to capture the *design intent*. Now if for example, the section thicknesses are altered, the vents will modify themselves to continue to provide air passage through the newly defined (thicker/thinner) section.

Futuristically speaking, it is in this stage that it is possible to build in a vast knowledge base which would dictate the convergence of the design solution by exercising control on the design variables based on prior experience in the design of similar parts.

The design stage typically involves the construction of curves, surfaces, solids or a combination of one or more of these types of entities. To do this, the CAD package utilizes knowledge in three fields: Design, Geometric modeling and Computer Graphics. For example, building 2D/3D wire frame models by representing points in space and connecting them by straight-line segments. The design idea dictates where in space, key points of the object are desired. We then transform this design requirement into a geometric model. This is in many ways similar to the sketch that a design engineer creates, only with a more exhaustive information content. While a traditional engineering drawing or sketch may show only one true (orthographic) viewpoint, essentially the one it is sketched in, the information in the geometric (solid) model is complete in all respects regardless of how it is being observed.

Further, it is the knowledge of computer graphics that achieves the task of generating a visual interface between the designer and the complete geometric model.

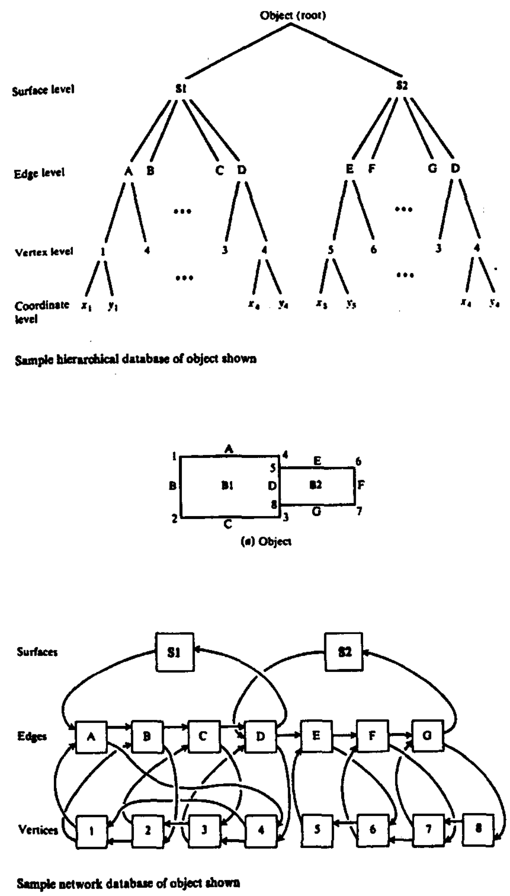


Figure 5: Typical Database structures [1]

It is this "complete" definition of the design that is harnessed efficiently by the integrated system and allows it to offer the use of various analysis and engineering tools seamlessly. The fact that most such tools require knowledge of this common set of geometric information led to the development of this integrated technology. To understand the concept, one can draw an analogy with control systems at this point. The fact that the design model is exhaustive in information content makes it possible to Feed-Forward the information into the subsequent stages of the Design process (See illustrations next). Now, it remains to be seen how feedback on design works. For now, we will assume that it is possible to update the upstream stages by propagating changes made in one of the downstream stages.

In the following illustrations we shall substantiate the above ideas, as well as demonstrate the concept of Full-Associativity introduced earlier as an important feature of Pro/Engineer.

The solid model completed in the design and modeling stage is now used to generate a standard Engineering Drawing (see Fig. 6). The process being largely standardized, it involves use of standard formats of sheet presentation and view placement. All this is automatically handled by the system. In fact the process is so simple, that drawings that used to take weeks to execute on the drawing board can now be completed in a matter of minutes once the solid model has been made.

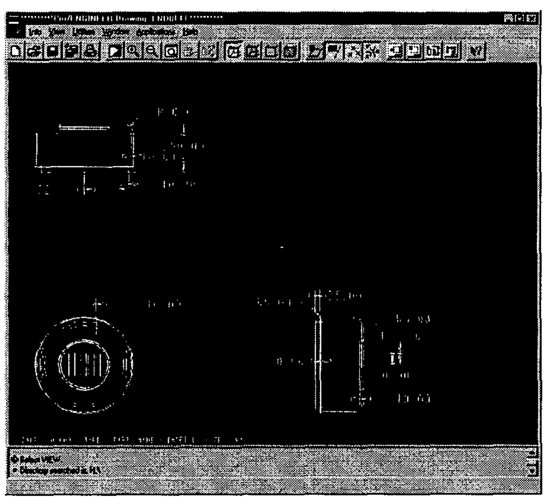

Figure 6: Engineering Drawing generated from the solid model

We now illustrate the seamless nature of the process by introducing a change in the product design, not at the modeling stage, but after engineering drawings have been generated.

Here we have changed the depth of the end bell cup. While it can be seen in the original sketch (Fig.1) that the depth is 250mm. We have increased it to 350 mm. Possibly to accommodate a larger cooling fan. This is done in the top orthographic view and is seen in the next illustration:

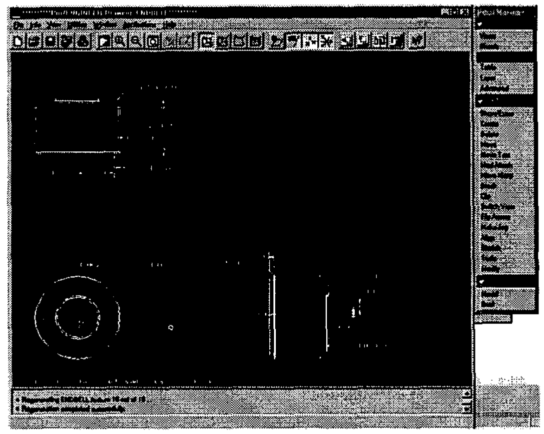

Figure 7: Change incorporated in the top view

This change made above, in the drawing generation stage, is now automatically propagated to all the other stages of the product development process without any interfacing difficulties.

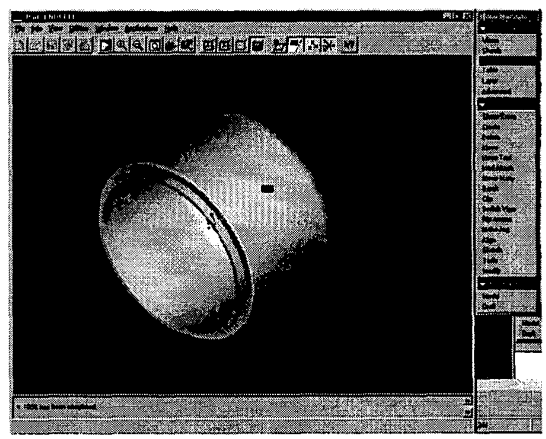

Figure 8: Effect of change made on the drawing, updates solid model

This enables the system to save enormous amounts of time and other resources. While we cannot show the effect on all the stages, upstream or downstream, for reasons of brevity, we illustrate the change effected on the solid model seen in Fig.8 Dimensions are chosen such as to exaggerate changes and make them more visible to the reader.

B. Elementary analysis (CAE)

Before the product goes into the development phase the design needs to be evaluated for various factors such as service stresses, temperature exposure, and residual stresses involved in the manufacturing process (example: Deep-Drawing) of the said product. . So we can have limitations e.g. bend-radii which can dictate changes in the design.

Finite Element techniques are increasingly being used for conducting such Engineering analyses. It is for this reason that this tool is included into integrated CAD/ CAE/ CAM/ PDM systems. In the attached illustration note the optimal distribution of mesh nodes throughout the object space. More importantly, note that the density of elements is higher in the areas of high stress concentration.

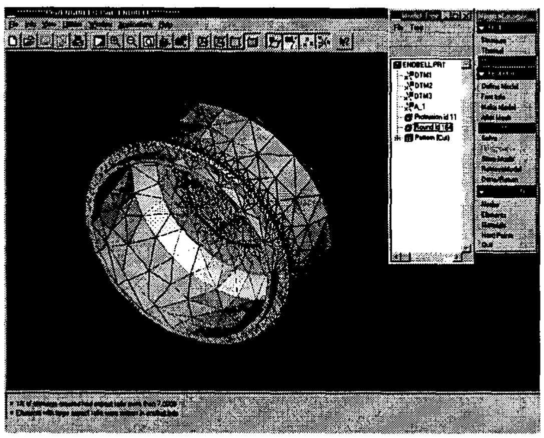

Figure 9: Finite Element Mesh generated for Mold Flow Analysis on the same Solid Model

In a completely general setting this stage typically involves one or more of the following: Mechanism Analysis (Kinematics and Dynamics), FEA (Finite Element Analysis), Sheet Metal Design etc.

C. Tooling Development Phase

Most available commercial CAD/CAM packages now allow users to model different types of tooling, like punch-press tools involving Punch-Die combinations, Injection Molds involving moving and fixed halves etc. by following a series of very simple steps. The time involved in this stage of the product development cycle is drastically cut down. This is made possible by the fact that now the Tooling Engineer need not design or model the dies explicitly and can derive the die models from the already modeled product. The system here provides all possible tooling considerations such as surface offsets, isotropic / anisotropic shrinkage allowances etc. All techniques involved in tooling design are elegantly implemented in such systems. In fact, the process of tooling development is now so simplified/systematized that tooling can be designed with very little or no experience.

D. Manufacturing

The integrated system is capable of generating manufacturing routines or NC sequences that when executed on a numerically controlled machine can complete the manufacturing of the desired part. This generation though not completely automated is very near to being so. The definition of the process plan being the major area requiring extensive and specialized knowledge of manufacturing methods. The technology of Computer Aided Process Planning CAPP is still in its infancy. Also, the huge amount of information that needs to be built into such a system is the major hindrance. For such a CAPP tool to function, a lot more knowledge has to be built into the solid model too. Feature based recognition systems are the first steps in the right direction. These will store information such as a particular feature being a hole, which in turn helps the system to identify the need for a drilling operation. While this is a very simple case, it serves the purpose of introducing the reader to the immense opportunities available to build in manufacturing specific knowledge into CAD/CAM systems.

The manufacturing sequences for now, are generated on parameter information provided by the user, like type of machine tool, type of operation i.e. drilling, milling etc., tooling used and desired approach for manufacturing.

The numeric data is then derived from the geometric model, which is already present as a database in the system from the very first stage of design (Fig. 5). The actual numerics for the NC sequences being calculated using this database along with manufacturing parameters e.g. Tool geometry, Step Over, Step Depth and Operation Type.

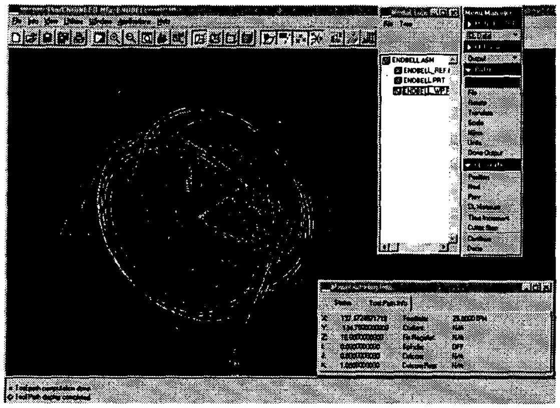

Figure 10: A Volume milling operation (Cutter Path displayed inside wire-frame model)

It is then possible to simulate the generated code, by automating the process of representation. This allows the user to check for errors in tool-path and evident losses like "air-cutting", gouging and machine collisions.

```
$$-> MFGNO / ENDBELL
PARTNO / ENDBELL_WP
$$-> FEATNO / 39
MACHIN / MILL, 01
UNITS / INCHES
LOADTL / 1
$$-> CUTTER / 25.000000
$$-> CSYS / 1.0000000000, 0.0000000000, 0.0000000000, 0.0000000000,  $
            0.0000000000, 1.0000000000, 0.0000000000, 0.0000000000,  $
            0.0000000000, 0.0000000000, 1.0000000000, 0.0000000000
SPINDL / RPM, 800.000000,  CLW
RAPID
GOTO / 0.0000000003, 231.4575131107, 10.0000000000
RAPID
GOTO / 0.0000000003, 231.4575131107, -209.0000000000
FEDRAT / 100.000000,  IPM
GOTO / 0.0000000003, 231.4575131107, -220.0000000000
CIRCLE / 0.0000000000, 0.0000000000, -220.0000000000,  $
0.0000000000, 0.0000000000, 1.0000000000,  231.4575131107
GOTO / 0.0000000003, 231.4575131107, -220.0000000000
GOTO / 0.0000000003, 226.2132034356, -220.0000000000
GOTO / 0.0000000003, 226.2132034356, -230.0000000000
CIRCLE / -0.0000000000, 0.0000000000, -230.0000000000,  $
0.0000000000, 0.0000000000, 1.0000000000,  226.2132034356
GOTO / 0.0000000003, 226.2132034356, -230.0000000000
GOTO / 0.0000000003, 226.2132034356, 10.0000000000
SPINDL / OFF
$$-> END /
FINI
```

Figure 11: A typical Cutter Location Source File (CLSF) on Pro/E for profiling the end-bell

There is an ongoing effort also to build in the knowledge of Metal cutting mechanics to more closely simulate the manufacturing process. We, the authors, are currently engaged in one such effort. Once the physics of the process is also built into such systems, it will be possible to achieve near-perfect manufacturing routines.

The full benefits of the integrated CAD/CAM system can only be achieved by a complete and efficient interfacing of this system with the production machines. This interfacing consists of the following important parts: First, establishing trouble free wired communications between computer systems running the CAD/CAM system and the controllers of the production centers. Secondly, interpretation of the generated NC Sequences into Machine readable/ executable code. This brings us to the requirement of Post-Processor development.

A Post Processor is software containing the most complete definition of the characteristics of a machine and the required format for its accompanying controller. This assumes importance during implementation of an integrated setup, as a separate Post Processor is required for each different type of machine/controller at a given facility. Needless to say, there are many companies that are not able to harness the technology fully, due to problems faced at this stage. Authors have experience in this field and are currently working on ironing out such kinks at companies like Raytheon Technical Services Corp.

Pro/Engineer has a generic Post-Processor module known as CAM/POST. We used this module to interface the system to one of our 3-Axis Milling machines, the HURCO CNC Vertical Mill with a KMB-1 controller. While the communication was setup with comparative ease due to support from the machine manufacturer, we found that most such machine tool makers do not provide any support for Post-Processor development.

A few salient features of this development are described here. The NC Programming format for the machine, meaning machine and controller hereafter, conformed to the EIA RS-274D. The machine axes definitions were the next critical aspect. In this case, as there were no rotating heads or rotary tables, the job was considerably easier due to the fact that all axes assignments were static i.e. unchanged for all movements. The machining plane definitions were also fixed. Apart from associating the standard codes to the appropriate movement commands in the CLSF e.g. G00 for RAPID, M6 for LOADTL etc. we had to ensure proper numerical representations for all NC words. Both of these can be well understood on comparison of the Machine code generated after Post processing to the NC Sequence presented in Fig.11.

```
%
N0 G70$
N5 T01 M6$
N10 G0 X0.0 Y231.4575 Z10.0 S800 M3$
N15 Z-209.0$
N20 G1 Z-220.0 F39.4$
N25 G17$
N30 G3 X0.0 Y231.4575 I0.0 J0.0$
N35 G1 Y226.2132$
N40 Z-230.0$
```

```
N45 G3 X0.0 Y226.2132 I0.0 J0.0$
N50 G1 Z10.0$
N55 M5$
N60 M2$
E
```

As is also evident from the machine code there are a lot of format related issues specific to every controller. Here the KMB-1 controller requires for example the "%" sign to denote start of a program, "$" sign to signify end of an NC Block, the "E" symbol denotes end of the NC program etc.

While it is difficult to present all the aspects and considerations of this development, we feel that these examples will go a long way to elucidate the concept. We do need to emphasize, however, that this development of Post-Processors is a one-time task that once successfully completed opens the doors to ample rewards in terms of the benefits related to implementing the integrated CAD/CAM system.

Another increasingly important technology is the method of Rapid prototyping. It is now possible to get very precise product prototypes very quickly. This is mostly done through a method called Stereo Lithography and the data required to be generated from the CAD system are now a standard format across the industry. A rapid prototype has, however, very little functional use i.e. it cannot replace the physical prototype for Life tests etc. Their typical uses are form and fit related.

E. Note on Optimization:

The process of optimization in product design involves a series of design loops. In a typical recursion, a design solution is obtained after which one of the design variables is modified to achieve a certain effect on the solution. This in turn, on evaluation leads to desired changes of the same or different variable. Thus, setting off another iteration, till a completely satisfactory solution emerges.

It is this ease of introducing design changes and propagating the effects to the subsequent stages, as well as earlier stages in development that make the integrated system lucrative for product development environments. A relevant paper by T.J.E.Miller and R.Rabinovici [5] involves developing algorithms that are particularly useful in integrated CAD software. The algorithms are applicable to the calculation of the back-EMF waveform of any winding distribution in all the main classes of radial-airgap brushless DC motors, together with the no-load core losses. The algorithms depend on an approximation of the airgap flux-density distribution, and include new methods based on the flux linkage and EMF waveforms of a single-turn coil wound around one tooth. They describe the methods used to calculate these waveforms and their application to the calculation of core loss and total winding EMF. This development and others [6] translate into the fact that generation of the design model of an electric motor can be automated completely starting only from the basic Electrical Engineering Specifications.

It is important to realize here that because of this tool it is possible to introduce radical changes into a particular part design (even very late in the development process) to make it better suited at the mechanism/assembly level scheme of things. Earlier, this would generally be avoided due to time delays involved in any such change, and hence end up as a compromised product. The fact that the user now has a powerful CAD/CAM package running on increasingly faster computer systems, undoubtedly results in making a plethora of options available to the designer and ensures a much better and optimized product design. In fact we can safely say that this system "*encourages*" change, without penalty, at any stage in the development cycle.

F. Data Exchange and Web Tools:

In this age of connectivity, CAD/CAM solutions cannot be deemed complete without a detailed interface to support Web based applications. The commercially available codes or CAD/CAM packages provide the possibility of being used as web server applications controlled by a web browser client. Also, they provide the user with ease of creating standard web specific output formats like HTML documents with embedded graphics e.g. JPG, CGM, TIFF, MPEG, GIF & VRML etc. This has its advantages, as it makes it easier for the user (i.e. the business organization) to convince the client. The client is also benefited as he has a visual representation that gives a feeling of reality, while the actual part is still in the stage of design conceptualization. All illustrations that are part of this paper are examples of how these tools can make technical communication easier and realistic. This technology enables for greater possibilities of product development through increased collaboration between designers developing the same parts as well as suppliers. They may even be located in different parts of the world and still be an effective part of the same team. It is important to note that till such time a truly integrated system is developed, different CAD/CAM systems will have to continue supporting different Data Migration Applications to ensure trouble free exchange of product design data to and from different originating systems.

## IV. CONCLUSION

The objective of the VPD process is to reduce the time and costs involved in the traditional methods of product design and development of Electrical Motors.

This paper explores the comprehensive nature of the technology. At the same time it experiments with the possibility of taking radically different design approaches, without compromising on the development times.

In Part IIIA, it discusses the possibility of enabling downstream functions to contribute their knowledge and expertise in the initial stages of product design. This is also illustrated in Figs. 5 & 6. Essential concepts in the design and modeling of products using CAD are also covered in this section.

In Part IIIB, a finite element mesh of the model is demonstrated. While it was difficult to include an explicit illustration of the full associativity of the software, we emphasize the fact that the entire CAD/CAM/CAE model updates automatically to changes in the geometry (improvements), and is ready to be re-analyzed. This is possible due to the fact that all stages of the process access and update a common database, evident from the illustrations.

In Part IIID, a near-complete snapshot of the Computer Aided Manufacturing stage of the process is presented. While it was not possible to include details on concepts like Rapid Prototyping etc., the interested reader is encouraged to find more literature in the references listed or get in touch with us.

Finally, the paper has been able to establish the concepts of an integrated CAD/CAM system. Our development of the illustrations has provided greater insight into the design and development process and how it can be further advanced to produce a true *no-holds-barred* Product Development Environment.

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