CONCURRENT ENGINEERING: Research and Applications

Concurrent Design and Manufacturing for Mechanical Systems

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Abstract: The conventional product development process employs a design-build-break philosophy. The sequentially executed product development process often results in a prolonged lead-time and an elevated product cost. The proposed concurrent design and manufacturing (CDM) paradigm employs physics-based computational methods together with computer graphics techniques for product design. This proposed approach employs Virtual Prototyping (VP) technology to support a cross-functional team in analyzing product performance, reliability, and manufacturing cost early in the product development stage; and in conducting quantitative trade-off for design decision making. Physical prototypes of the product design are then produced using Rapid Prototyping (RP) technique primarily for design verification purposes. The proposed CDM approach holds potential for shortening the overall product development cycle, improving product quality, and reducing product cost. A software tool environment that supports CDM for mechanical systems is being built at the Concurrent Design and Manufacturing Research Laboratory (http://cdm.ou.edu) at the University of Oklahoma. A snapshot of the environment is illustrated using a two-stroke engine example. This paper presents three unique concepts and methods for product development: (1) bringing product performance, quality, and manufacturing cost together in early design stage for design considerations, (2) supporting design decision-making through a quantitative approach, and (3) incorporating rapid prototyping for design verification through physical prototypes.

Key Words: concurrent engineering, virtual prototyping, rapid prototyping, design trade-off, virtual manufacturing.

1. Introduction

The conventional product development process that is conducted sequentially suffers from the problem of design paradox [1]. This refers to the dichotomy or mismatch between the design engineers' knowledge about the product and the number of decisions to be made (flexibility) throughout the product development cycle, as illustrated in Figure 1. Design decisions must be made in the early design stage when the product being designed is not very well understood. Consequently, engineering changes are frequently requested in later product development stages, when product design evolves and is better understood, to correct design decisions made earlier.

The conventional product development process employs a design-build-break philosophy. Product performance and reliability assessments rely heavily on product hardware tests. This process involves fabricating functional prototypes of the product and usually requires conducting lengthy and expensive hardware tests for evaluations of product performance and reliability. Fabricating prototypes usually involves manufacturing process planning, and fixtures and tooling for a very small amount of production. The process could be expensive and lengthy, especially when a design change is requested to correct problems found in hardware tests.

The conventional product development practices tend to separate design and manufacturing engineers. Often, manufacturability of a product is not considered in design. Manufacturing related issues usually appear when the product design is finalized and tests are completed. Design defects related to manufacturing found in the process planning or production stage are usually too late to be corrected. Consequently, more manufacturing procedures are necessary for production, resulting in elevated product cost.

With this highly structured and sequential process, the product development cycle tends to be extended, cost is elevated, and product quality is often compromised to avoid further delay. The cost and number of engineering change requests (ECR) throughout the product development cycle are often related in conforming to the pattern shown in Figure 2. It is reported that only 8% of the total product budget is spent for design, however, design in the early stage determines 80% of the lifetime cost of the product [2].

Apparently, today's industries will not survive the worldwide competition unless they introduce new products with better quality, at lower cost, and with shorter lead time. Many different approaches and concepts have been proposed over the years, with a common goal—shorten product development cycle, improve product quality, and reduce product cost.

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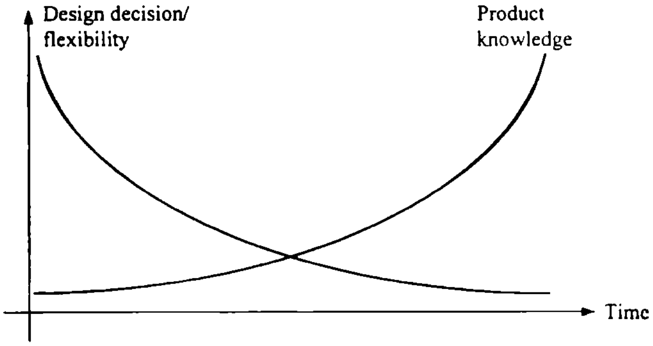


Figure 1. Design paradox.

A number of approaches proposed are along the line of Virtual Prototyping [3]. Virtual Prototyping is a simulation-based method used to help engineers understand product behavior and make design decisions in a virtual environment. The virtual environment is a computational framework in which the geometric and physical properties of products are accurately simulated and represented. A number of successful stories have been reported very recently, such as the Boeing 777 jetliner, General Motors' locomotive engine, Chrysler's automotive interior design, and Stockholm's Metrocar 2000, to name a few [3]. In addition to Virtual Prototyping, the Concurrent Engineering (CE) concept and methodology have been studied and developed with emphasis on subjects such as product life cycle design, DFX (Design for X-abilities), integrated product and process development (IPPD), and six-sigma [4].

Although significant research has been conducted in improving the product development process and successful stories have been reported, U.S. industry at large is not taking advantage of these product development paradigms. The main reason is that small and mid-size companies cannot afford to develop an in-house computer tool environment like Boeing and the Big Three did. On the other hand, commercial software tools are not tailored to meet the specific needs of the company. Commercial tools often lack proper engineering capabilities to support specific product development needs. Most of them are not integrated to support an industry's needs. Therefore, companies are using commercial

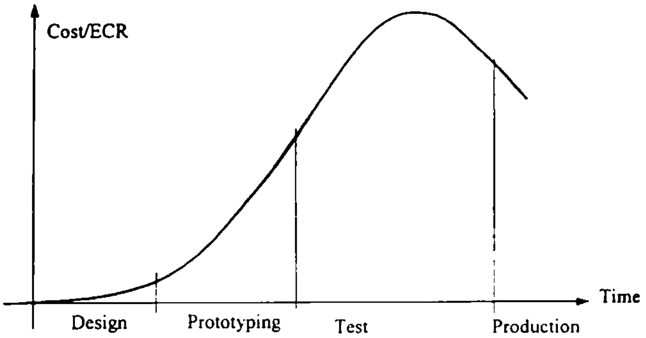


Figure 2. Cost/ECR vs. time in conventional design cycle.

tools to support segments of their product development without taking full advantage of the new design paradigms.

The proposed CDM approach does not supersede any of the approaches discussed. The proposed approach is indeed a realization of Concurrent Engineering through Virtual Prototyping with a systematic and quantitative method for design decision making. Moreover, the proposed approach specializes in the performance and reliability assessment and improvement of complex, large-scale, computer-intensive mechanical systems. This CDM paradigm also brings DFM (Design for Manufacturability), DFMA (Design for Manufacturing and Assembly), and manufacturing cost estimates through virtual manufacturing process planning and simulation for design considerations.

The objective of the research is to develop CDM methods and tool environments that support a cross-functional team to simulate and design mechanical products concurrently in the early design stage. Consequently, better quality products can be designed and manufactured with less cost. With intensive knowledge of the product gained from simulations, better design decisions can be made, hence, breaking the aforementioned design paradox. With the advancement of computer simulations, more hardware tests can be replaced by computer simulations, therefore, reducing cost and shortening product development time. The desirable cost and ECR distributions throughout the product development cycle shown in Figure 3 can be achieved through the CDM paradigm.

The CDM software environment is being built using existing Computer-Aided Design (CAD)/Computer-Aided Engineering (CAE)/Computer-Aided Manufacturing (CAM) as the base, and integrating discipline-specific software tools that are commercially available for specific simulation tasks. The first set of CAD/CAE/CAM being incorporated is Pro/ENGINEER [5] and its CAE/CAM modules. The main technique involved in building the CDM environment is tool integration. Tool integration techniques, including product data model, wrapper, engineering views, and design process management, have been developed [6] and will be briefly described later in this paper. This integrated CDM tool environment provides small and mid-size companies with an opportunity for conducting efficient product development through the CDM paradigm. The environment is flexible so that additional engineering tools can be incorporated with least effort. In addition, the basis for tool integration, such as product data management (PDM), has been well established in the commercial CAD tools; no wheel is re-invented.

This paper presents three main concepts and methods for product development: (1) bringing product performance, quality, and manufacturing cost in the early design stage through Virtual Prototyping for design considerations, (2) supporting design decision-making through a quantitative approach for both concept and detail designs, and (3) incorporating product physical prototyping for design verification via Rapid Prototyping. The paper is organized as follows. The proposed CDM paradigm is introduced first to provide

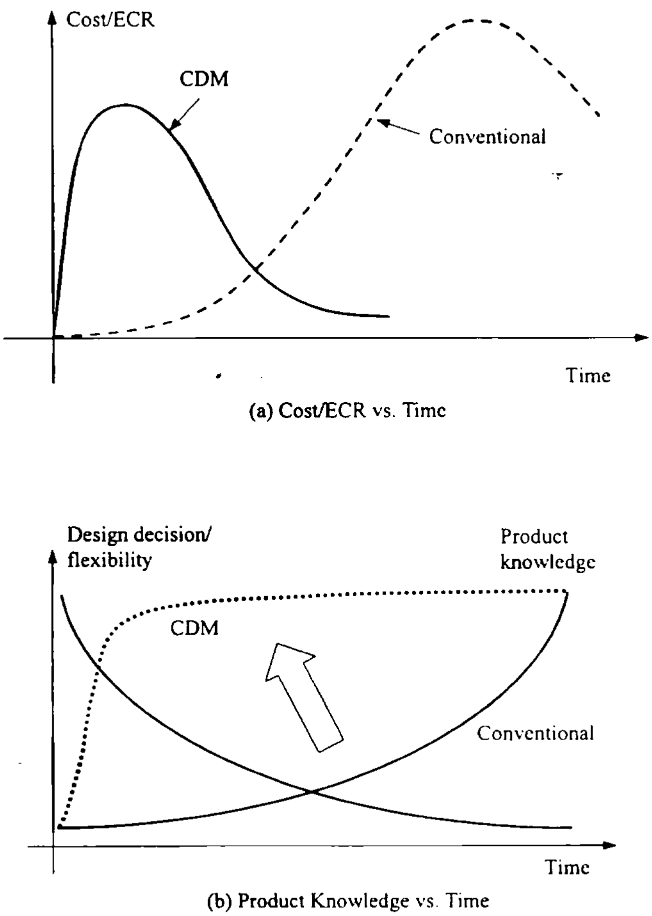


Figure 3. Cost/ECR and product knowledge vs. time of the CDM design cycle.

an overview of the idea. Components that constitute the paradigm, including Knowledge-Based Engineering (KBE) [7], Virtual Prototyping, and Rapid Prototyping are presented next. Design of a simplified airplane engine is presented to illustrate the proposed approach and a snapshot of the CDM environment. Conclusions and future work are discussed last. Presentation of the paper will be a mix of CDM concept and tool environment.

2. Concurrent Design and Manufacturing

The proposed CDM paradigm consists of Virtual Prototyping for product design, and Rapid Prototyping for fabricating product physical prototypes, as shown in Figure 4. In the proposed approach, a product design concept is first created in solid model form by design engineers, using CAD tools. The initial product is often established based on designer's experience and legacy data of previous product lines. It is highly desirable to capture and organize the experience and legacy data to support decision making in a discrete form, in order to realize an initial concept design. The Knowledge-Based Engineering (KBE) that computerizes knowledge about certain product domain to support design engineers to arrive at a solution to a design problem from the product domain is desirable to support the concept design. In addition, a KBE system integrated with a CAD tool will directly generate a solid model of the concept design that directly serves the downstream design and manufacturing simulations.

With the product solid model represented in CAD, simulations for product performance, reliability, and manufacturing process can be conducted. The product development task and the cross-functional team are decomposed according to engineering disciplines and expertise. Based on a centralized CAD product model, simulation models can be derived with proper simplifications and assumptions. However, a one-way mapping that governs changes of CAD models to those of simulation models must be established for rapid simulation model updates [8]. The mapping maintains consistency between CAD and simulation models throughout the product development cycle.

Product performance, reliability, and manufacturing process can then be simulated concurrently. Product perfor-

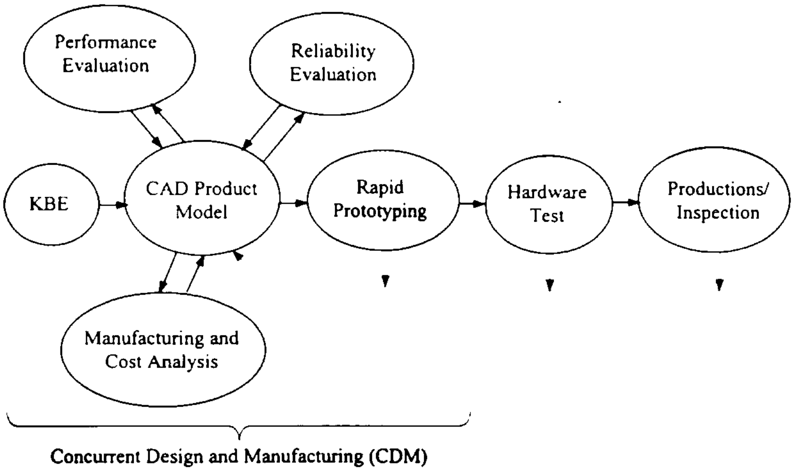


Figure 4. Concurrent design and manufacturing process.

mance, quality, and cost obtained from multi-disciplinary simulations are brought together for review by the cross-functional team. Design variables, including geometric dimensions and material properties of the product CAD models, that significantly influence the product performance, quality, and cost are identified by the cross-functional team in the CAD product model. These key performance, quality, and cost measures, as well as design variables constitute a product design model. With such a design model, a systematic design approach, including parametric study for concept design and trade-off study for detail design, can be conducted to improve the product with a minimum number of design iterations.

The product designed in the virtual environment can then be fabricated using Rapid Prototyping machines for physical prototypes directly from product CAD solid models, without tooling and process planning. The physical prototypes provide the cross-functional team with an opportunity for design verification and assembly checking. Change requests made at this point can be accommodated in the virtual environment without high cost and delay.

The physics-based simulation technology potentially minimizes the needs for product hardware tests. Due to substantial modeling and simulations performed, unexpected design defects encountered during the hardware tests will not be common, thus, minimizing the feedback loop for design modifications. Moreover, production process will be smooth since the manufacturing process has been planned and simulated. Potential manufacturing-related problems should have been largely addressed in earlier stages.

Pro/ENGINEER [5] has been employed first as the base for the CDM environment. In addition to its superior solid modeling capability based on the parametric technology [9], Pro/MECHANICA supports simulations of nominal engineering problems, including structural, thermal, and motion. Moreover, CAM capabilities implemented in modules like Pro/MFG, Pro/SHEETMETAL, and Pro/WELDING, provide an excellent basis for manufacturing process planning and simulations. Additional tools are being integrated to support modeling and simulation of broader engineering problems encountered in general mechanical systems.

3. Virtual Prototyping

Virtual Prototyping is the backbone of the proposed CDM paradigm. Virtual Prototyping presented in this paper consists of constructing a parameterized CAD product model, conducting product performance simulations and reliability evaluations using CAE software, and carrying out manufacturing simulations and cost estimate using CAM software. Product modeling and simulation using integrated CAD/CAE/CAM software is the basic and common activity involved in Virtual Prototyping. However, a systematic design method, including parametric study and design trade-off, is indispensable for design decision making.

3.1 Parameterized CAD Product Model

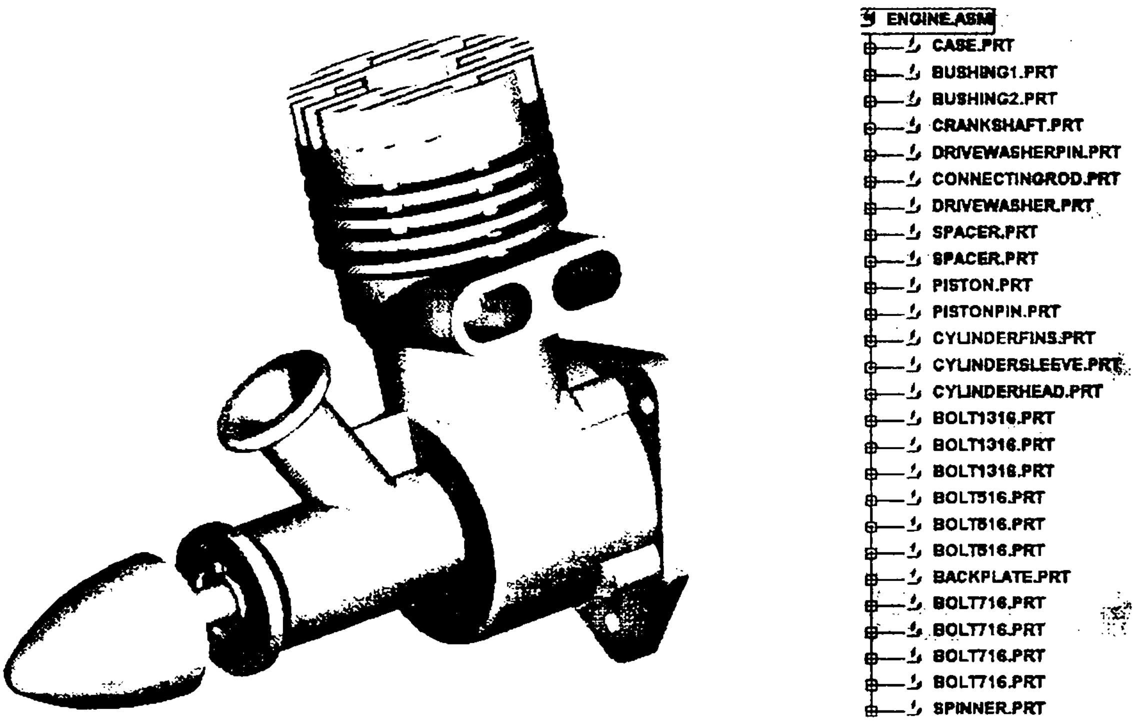
A parameterized product model in CAD forms the basis of the proposed CDM process. The product model evolves into a higher fidelity level from concept to detail design stages [8]. In the concept design stage, a considerable portion of the product may contain non-CAD representation when gross motion, for example, of the mechanical system is sought. The non-CAD data may include engine, tire, and transmission if a ground vehicle is being designed. Engineering characteristics of the non-CAD parts and assemblies are usually described by engineering parameters, physics laws, or mathematics equations. This non-CAD representation is often added to the product model in the concept design stage for a complete product model. As the design evolves, non-CAD parts and assemblies are refined into solid model forms for subsystem and component designs as well as manufacturing process planning. A primary challenge in conducting product performance simulations is generating simulation models and maintaining consistency between CAD and simulation models through the mapping. Model generation and potential difficulty involved in structural and dynamic simulations are discussed next, in which an airplane engine model in detailed design stage shown in Figure 5 is used for illustration.

3.1.1 PARAMETERIZED PRODUCT MODEL

A parameterized product model defined in CAD allows the design engineers to conveniently explore design alternatives for complicated mechanical products. The CAD product model is parameterized by defining dimensions that govern the geometry of parts through geometric features and establishing relations between dimensions within part and across parts. Through dimensions and relations, changes can be made by simply modifying a few dimension values. Changes will be propagated automatically throughout the mechanical product following the dimensions and relations. An engine example with a change in its bore diameter is shown in Figure 6 to illustrate the change propagation through parametric dimensions and relationships.

3.1.2 STRUCTURAL ANALYSIS MODELS

For product structural analysis, finite element analysis (FEA) models must be generated. In addition to structural geometry, loads, boundary conditions, and material properties can be conveniently defined in the CAD model. Most CAD tools are equipped with fully automatic mesh generation capability. This capability is convenient but often leads to large size FEA models with significant geometric discrepancy at the part boundary. An engine connecting rod example meshed using Pro/MESH with defaults mesh parameters is shown in Figure 7(b). The FEA model consists of 1,270 nodes and 4,800 tetrahedron elements, yet still reveals discrepancy to the true CAD geometry. Moreover, mesh distortion due to large deformation of the structure, such as hyperelastic problems, often causes FEA to abort prema-



(a) CAD Model (b) Model Tree

Figure 5. Airplane engine model.

turely. Semi-automatic mesh generation is more realistic, therefore, MSC/PATRAN [10] and HyperMesh [11] are being integrated into the CDM environment for mesh generation.

In general, p-version FEA [12] is more suitable for structural analysis in terms of minimizing the gap in geometry between CAD and finite element models and lessening the tendency in mesh distortion. As shown in Figure 7(c), the same connecting rod is meshed with 568 tetrahedron p-elements, using Pro/MECHANICA with a default setting. A one-way mapping between changes of CAD geometric dimensions and finite element mesh for both h- and p-FEAs can be established through a design velocity field [13]. The design velocity field allows directly and automatically generating finite element mesh of new designs.

Another issue worthy to investigate is the simplification of 3-D solid models to surface (shell) or curve (beam) models for analysis. Capabilities that semi-automatically convert 3-D thin shell solids to surface models are available, for example in Pro/ENGINEER. Converting slender and long solids to beam models is not yet available.

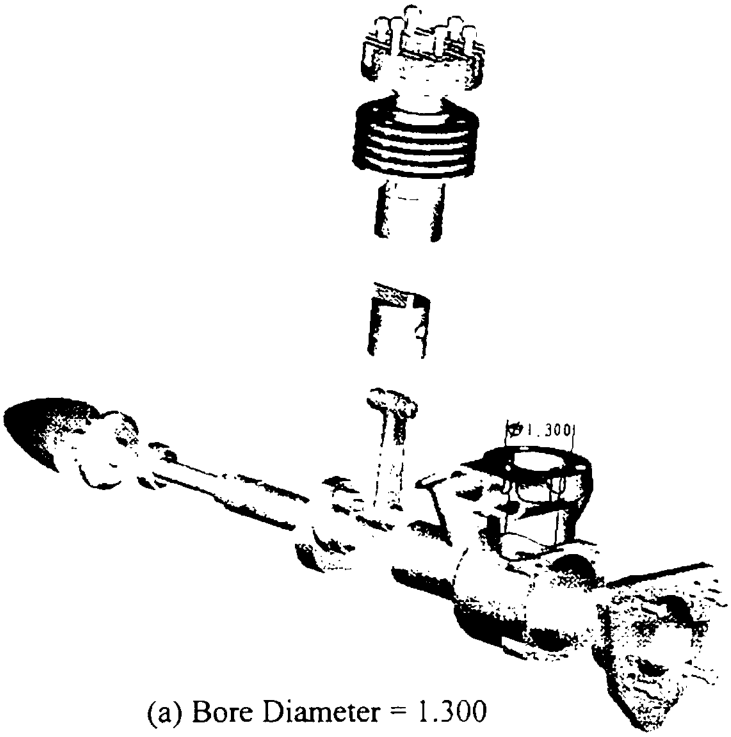
3.1.3 SYSTEM MOTION SIMULATION MODELS

Motion modeling involves regrouping parts and assemblies of the mechanical system in CAD as bodies and often introducing non-CAD components to support a multi-body dynamic simulation [14]. Engineers must define joints or force connections between bodies, including joint type and reference coordinates. Mass properties of each body are computed by CAD with the material properties specified. Integration between Pro/MECHANICA Motion and Pro/ENGINEER is excellent. Design changes made in geometric dimensions propagate to the dynamic model seamlessly. As an example, the motion inside an airplane engine is modeled as a slider crank mechanism in Pro/MECHANICAL Motion as shown in Figure 8.

A common mistake made in creating dynamic simulation models is selecting improper joints to connect bodies. Introducing improper joints creates an invalid or inaccurate model that does not simulate the true behavior of the mechanical system. Intelligent modeling capability that automatically specifies joints in accordance with assembly relations defined between parts and subassemblies in solid models is being developed, for example, DesignWorks [15].

3.2 Product Performance Analyses (Virtual Prototyping)

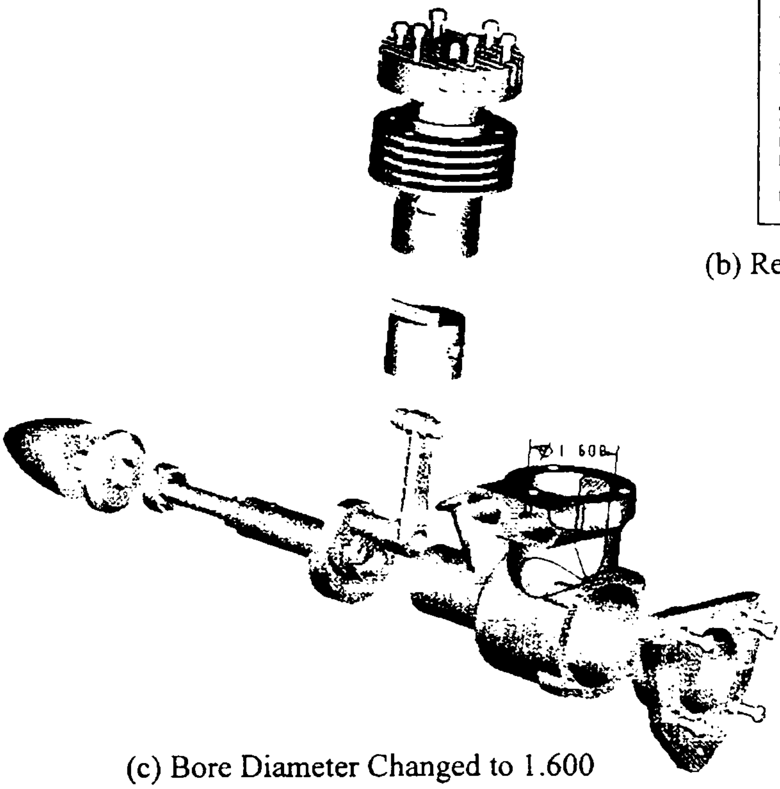
Product performance evaluation using physics-based simulation in the computer environment is usually referred to as Virtual Prototyping. With the advancement of simulation technology, more engineering questions can be answered realistically through simulations, thus minimizing hardware tests. However, key questions still cannot be answered for sophisticated engineering problems, for example, vehicle crashworthiness. Although Virtual Prototyping will proba-



(a) Bore Diameter = 1.300

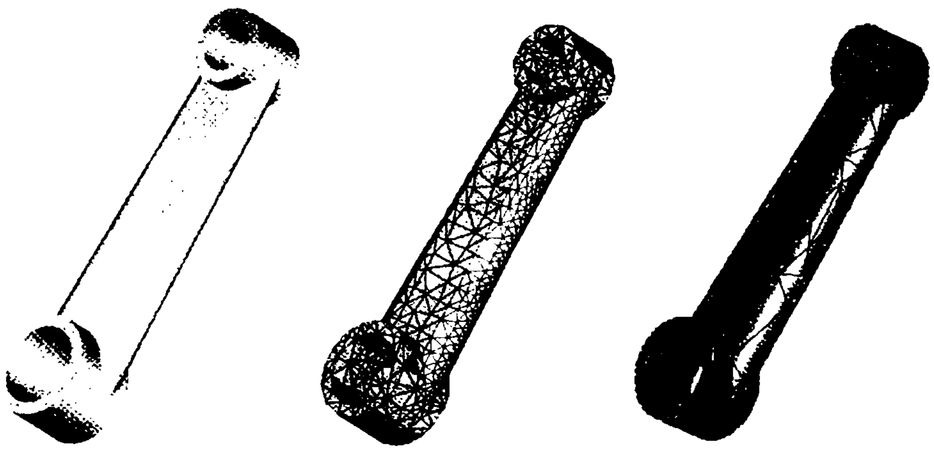
RELATION	PARAMETER	NEW VALUE
/*** Relations for ENGINE		
/* CASE		
D55 0=D46 0 D55 0	1 416000e+00	
D43 0=D46 0/2+0 424	D43 0	1 132000e+00
D40 0=D46 0/2+0 208667	D40 0	9 166670e-01
D0 0=D40 0-0 002	D0 0	9 146670e-01
D1 0=D40 0+0 124667	D1 0	1 041334e+00
D22 0=D1 0+D0 0-0 208	D22 0	1 748001e+00
D45 0=D22 0	D45 0	1 748001e+00
D47 0=D46 0/2+0 833	D47 0	1 541000e+00
D65 0=D46 0/2-0 332	D65 0	3 760000e-01
D66 0=D46 0/2+0 02133	D66 0	7 293300e-01
D113 0=D46 0/2	D113 0	7 080000e-01
D85 0=D0 0+0 40188	D85 0	1 316547e+00
D156 0=D0 0+D1 0	D156 0	1 956001e+00
D203 0=D0 0+D1 0	D203 0	1 956001e+00
D132 0=D46 0/2	D132 0	7 080000e-01
D282 0=(D46 0/2+D43 0)/2	D282 0	9 200000e-01
/* CRANKSHAFT		
D12 6=(D46 0/2-0 44444)*2	D12 6	5 271200e-01
/* CONNECTING ROD		
D27 10=D46 0/2-23333	D27 10	4 746700e-01
/* CYLINDER FINS		
D42 26=D282 0	D42 26	9 200000e-01
D45 26=D282 0	D45 26	9 200000e-01
D0 26=D46 0/2	D0 26	7 080000e-01
D1 26=D0 26+0 122	D1 26	8 300000e-01
D2 26=D43 0+0 118	D2 26	
1 250000e+00		
/* PISTON		
D1 16=D46 0/2-0 0827	D1 16	6 253000e-01
D7 16=D1 16-0 2413	D7 16	3 840000e-01
D22 16=D1 16-0 0653	D22 16	5 600000e-01
D19 16=D22.16*2-0 287	D19 16	8 330000e-01
/* CYLINDER SLEEVE		
D5 28=D46 0/2	D5 28	7 080000e-01
D7 28=D46 0-0 165	D7 28	1 251000e+00
D3 28=D46 0/2+0 08333	D3 28	7 913300e-01
/* CYLINDER HEAD		
D141 30=D282 0	D141 30	9 200000e-01
D123 30=D7 16-D8 16/2	D123 30	3 420000e-01
D0 30=D2 26	D0 30	
1 250000e+00		
D1 30=D1 16	D1 30	6 253000e-01

(b) Relations of Geometric Dimensions



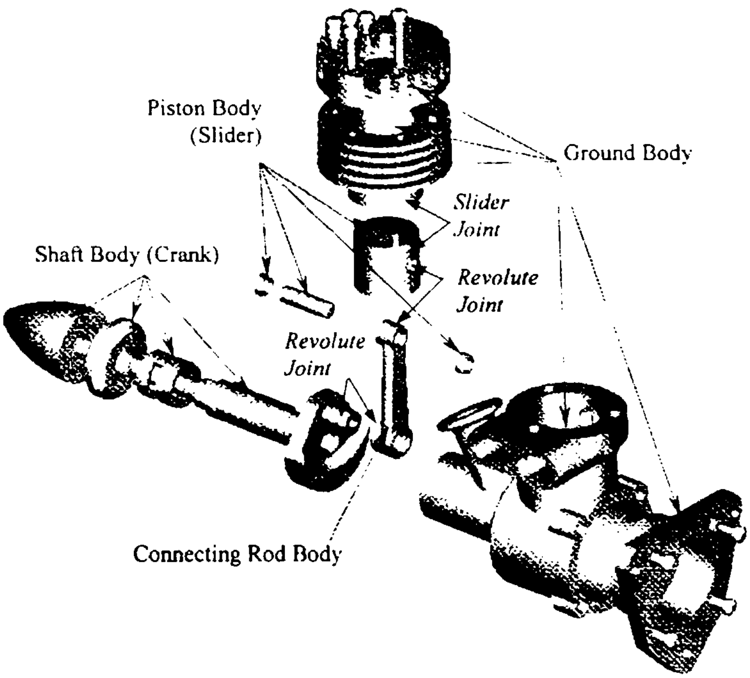
(c) Bore Diameter Changed to 1.600

Figure 6. Example of design change propagation.

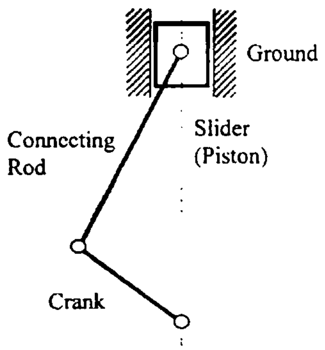


(a) CAD Solid Model (b) h-Finite Element Mesh (c) p-Finite Element Mesh

Figure 7. Finite element meshes of connecting rod.



(a) Definition of Motion Model



(b) Schematic View of the Motion Model

Figure 8. Engine motion model.

bly never replace hardware tests completely, savings achieved by conducting Virtual Prototyping for less sophisticated problems are significant and beneficial.

3.2.1 MOTION ANALYSIS

System motion simulations include workspace analysis (kinematics), rigid- and flexible-body dynamics, and inverse dynamic analysis. Pro/MECHANICA Motion based on theoretical work of Reference [16] mainly supports kinematics and rigid-body simulations for mechanical subsystems. Mechanical system simulation, such as a vehicle moving on a user-defined terrain, is not properly supported in Pro/MECHANICA Motion. General-purpose dynamic simulation tools, such as Dynamic Analysis and Design Systems (DADS) [17], are more desirable for simulation of general mechanical systems. In addition to Pro/MECHANICA Motion, DADS is being integrated into the CDM environment.

One of the current limitations in motion simulation tools is lack of reasonable capability for flexibility body dynamic analysis. Flexible body dynamics capability will accurately simulate mechanical systems with significant deformation in its components. Active research is being conducted in flexible body and work space areas, such as in Reference [18].

3.2.2 STRUCTURAL ANALYSIS

Pro/MECHANICA Structure supports linear static, vibration, and buckling analyses using p-version FEA [12]. General-purpose finite element codes, such as MSC/NASTRAN [19], are being integrated into the CDM environment to support general FEA for structural problems, such as non-linear, plasticity, transient dynamics, etc. Newly developed meshless methods [20] hold promise for avoiding finite element mesh distortion in large deformation problems. Multiphase problems, such as acoustic and aero-structural, are well supported by specialized tools, such as SYSNOICE [21]. LS-DYNA [22] is currently one of the best codes for problems of non-linear plastic dynamics with friction, especially crashworthiness. These special codes are being investigated for possible incorporation into the CDM environment.

3.2.3 FATIGUE AND FRACTURE ANALYSIS

Fatigue and fracture problems are commonly encountered in mechanical components due to repeated mechanical or thermal loads. MSC/PATRAN Fatigue [23] with underline computational engine developed by nCode [24] is being integrated into the CDM environment. Both high- and low-cycle fatigue analyses are available in MSC/PATRAN Fatigue. A critical plane approach is available in MSC/PATRAN Fatigue for fatigue life prediction due to general multi-axial loads. An excellent integration is available among PATRAN (modeling and FEA), PATRAN Fatigue, and MSC/NASTRAN (FEA).

Note that additional capabilities, such as thermal analysis, combustion, and computational fluid dynamics (CFD), can be added to meet specific needs in analyzing the mechanical products. Integration of additional engineering disciplines will be briefly discussed in Section 3.5.

3.3 Product Reliability Evaluations

Product reliability evaluations in the CDM environment currently focus on probability of failure of a specific event. The failure event corresponds to a product performance measure, such as fatigue life of a mechanical component. For reliability analysis of a single failure event, the failure event or failure function is defined as [25]

$$g(\boldsymbol{X}) = \psi(\boldsymbol{X}) - \psi_0 \tag{1}$$

When the product performance does not meet the requirement, i.e., $\psi(\boldsymbol{X}) \leq \psi_0$, the event fails. Therefore, the probability of failure P_f of the particular event $g(\boldsymbol{X}) \leq 0$ is

$$P_f = P[g(\boldsymbol{X}) \leq 0] \tag{2}$$

Given the joint probability density function $f_X(x)$ of the random variables $\boldsymbol{X}$, the probability of failure for a single failure event of a mechanical component can be expressed as

$$P_f = P(g(\boldsymbol{X}) \leq 0) = \iint\limits_{g(X)\leq 0} \ldots \int f_X(x)dx \tag{3}$$

The probability of failure of Equation (3) is commonly evaluated using the Monte Carlo method, or the first- or second-order reliability method (FORM or SORM) [26]. Once the failure probabilities of several failure events in subsystems or components are computed, system reliability can be obtained by, for example, the fault-tree analysis [27]. No general-purpose software tool for reliability analysis of general mechanical systems is commercially available yet. Currently, an in-house computational code with an approximation technique [28] is serving for the computations. At the same time, the Numerical Evaluation of Stochastic Structures Under Stress (NESSUS) [29] is being inquired. With the probability of failure, critical quality design criteria, such as mean-time-between-failure (MTBF), can be computed [27].

Two main challenges exist in reliability analysis: (1) realistic distribution data are difficult to get and usually are not available in the early stage, and (2) failure probability computations are often expensive. The first challenge may be alleviated by employing legacy data of previous product lines. Approximation techniques, such as in Reference [28], must be employed to make the computation affordable even for an individual failure event within a mechanical component.

3.4 Product Virtual Manufacturing

Virtual manufacturing addresses issues of design for manufacturability (DFM) [4] and design for manufacturing and assembly (DFMA) [30] in early product development stage. In the CDM paradigm, DFM and DFMA are performed by conducting virtual manufacturing and assembly, for example, using Pro/MFG. DFM and DFMA of the product are verified through animations of the virtual manufacturing and assembly process.

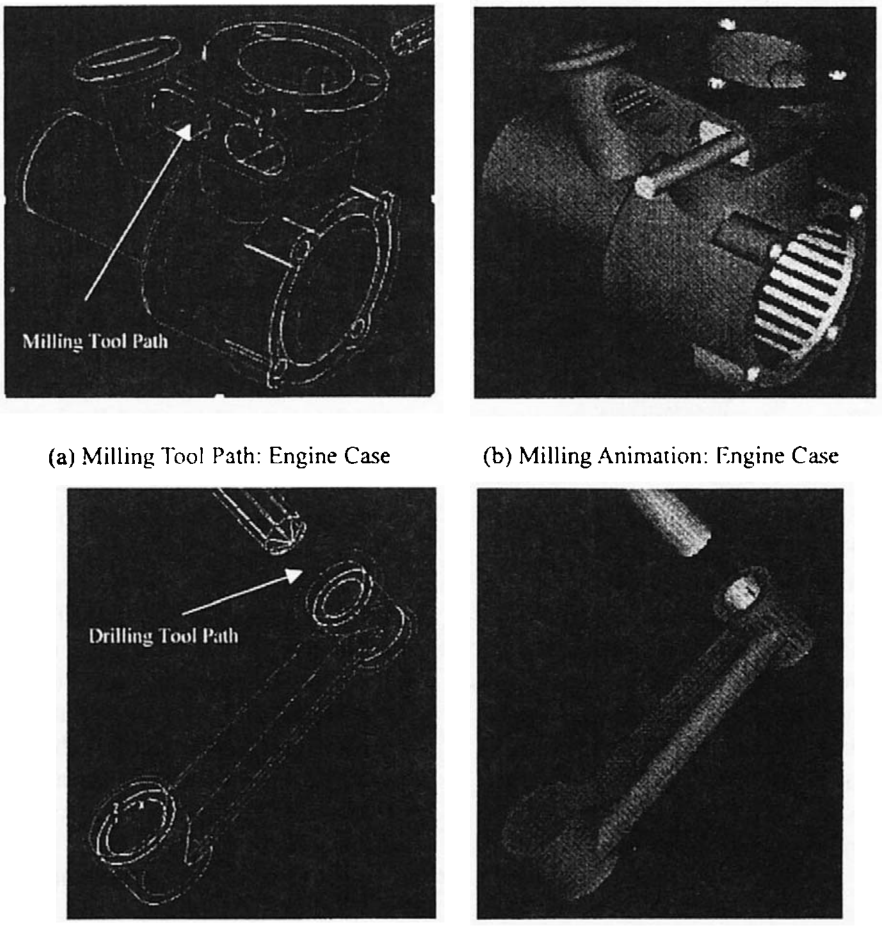
Pro/MFG is a Pro/ENGINEER module supporting the virtual machining process, including milling, drilling, and turning. By bringing part design into Pro/MFG, defining workpiece, workcell, fixtures, cutting tool, and cutting parameters, Pro/MFG automatically generates tool path [for example, Figures 9(a) and 9(c)], animates the machining process [Figures 9(b) and 9(d)], calculates machining time, and produces CL data. The CL data can be post-processed for CNC codes. In addition, casting, sheet metal, molding, and welding can be simulated using Pro/CASTING, Pro/SHEETMETAL, Pro/ MOLD, and Pro/WELDING, respectively. With such virtual manufacturing process planning and animations, manufacturability of the product design can be verified.

The DFMA tool [30] developed by Boothroyd Dewhurst, Inc., supports the cross-functional team to quantify product assembly time and labor costs. The tool also challenges the team to simplify the structure of the products and thereby reduces product costs as well as assembly costs. This tool is being investigated for integration into the CDM environment.

One of the limitations in virtual manufacturing, such as using Pro/MFG, is that chip formation [31], a primary consideration in CNC, is not incorporated into the simulation. In addition, machining parameters, such as power consumption, machining temperature, and tool life that contribute to manufacturing cost are not being simulated.

3.5 Tool Integration

Techniques that support the tool integration have been largely developed [6]. Main techniques include parameterized product data model, engineering views, tool wrappers, and design process management. Parameterized product data model represents engineering data that are needed for conducting Virtual Prototyping for the mechanical system. The main sources that constitute the product data model will be CAD and non-CAD models. The product data model evolves throughout the product development cycle. Engineering views allows engineers from various disciplines to view the product with their own perspectives. Through engineering views, engineers will create simulation models that



(a) Milling Tool Path: Engine Case (b) Milling Animation: Engine Case

(c) Drilling Tool Path: Connecting Rod (b) Drilling Animation: Connecting Rod

Figure 9. Virtual machining process.

are consistent to the product model by simplifying the CAD model, adding non-CAD product representation, and establishing mapping. Tool wrappers provide two-way data translation and transmission between engineering tools and product data model. Design process management provides the team leader with a tool to monitor and manage design process. When a new tool of an existing discipline, for example ANSYS [32] for structural FEA, is to be integrated, a wrapper for ANSYS must be developed. Three main tasks must be carried out when a new engineering discipline, for example Computational Fluid Dynamics (CFD), is to be added to the environment. First, the product data model must be extended to include engineering data needed to support CFD. Second, engineering views must be added to allow design engineers to generate CFD models. And finally, wrappers must be developed for specific CFD tools. More details about the integration techniques can be found in Reference [6].

3.6 Design Decision Making

Product performance, reliability, and manufacturing cost that are evaluated using simulations can be brought to the cross-functional team for review. Product performance and reliability will be checked against product specifications that are defined and evolved from the beginning of the product development process. Manufacturing cost obtained from the virtual manufacturing simulations can be added to product cost. The cross-functional team must address areas of concern identified in product performance, reliability, and manufacturability. The team must also identify a set of design variables that influence these areas of concern. Design modifications can then be conducted. In the past, Quality Functional Deployment (QFD) [27] has been largely employed to conduct design modification by assigning qualitative weighting factors to relate product performance and design changes. In CDM, a systematic and quantitative approach is employed for design modifications [33].

3.6.1 DESIGN PROBLEM FORMULATION

Before a design can be improved, design objectives must be defined. Design objectives are often presented in a mathematical form, typically:

$$\text{Minimize:} \quad C(\mathbf{b}) \tag{4a}$$

$$\text{Subject to:} \quad \psi_i(\mathbf{b}) \le \psi_i^u \quad i = 1, m \tag{4b}$$

$$P_{f_j}(\mathbf{b}) \le P_{f_j}^u \quad j = 1, n \tag{4c}$$

$$b_k^l \le b_k \le b_k^u \quad k = 1, p \tag{4d}$$

Note that Equations (4b) and (4c) are called constraint functions. In CDM, design variables are associated with dimensions of geometric features and part material properties in the parameterized CAD models. The feature-based design parameters serve as the common language to support parametric study and design trade-off.

3.6.2 DESIGN SENSITIVITY ANALYSIS

Before quantitative design decisions can be made, design sensitivity analysis (DSA) that computes derivatives of performance measures, including product performance, failure probability, and manufacturing cost, with respect to design variables must be conducted. Dependence of performance measures on design variables is usually implicit. Expressing product performance in terms of design variables in a mathematical form is not straightforward. Analytical DSA methods combined with numerical computations have been developed mainly for structural response [13], and fatigue and fracture [34]. Recently, DSA for failure probability with respect to both deterministic and random variables has been developed [33]. In addition, DSA and optimization using meshless methods have been developed for large-deformation problems [35].

For problems such as motion and manufacturing cost, where premature or no analytical DSA capability is available, finite difference method is the only choice. The finite difference method is expressed in the following equation:

$$\frac{\partial \psi}{\partial b_j} \approx \frac{\psi(\mathbf{b} + \Delta b_j) - \psi(\mathbf{b})}{\Delta b_j} \tag{5}$$

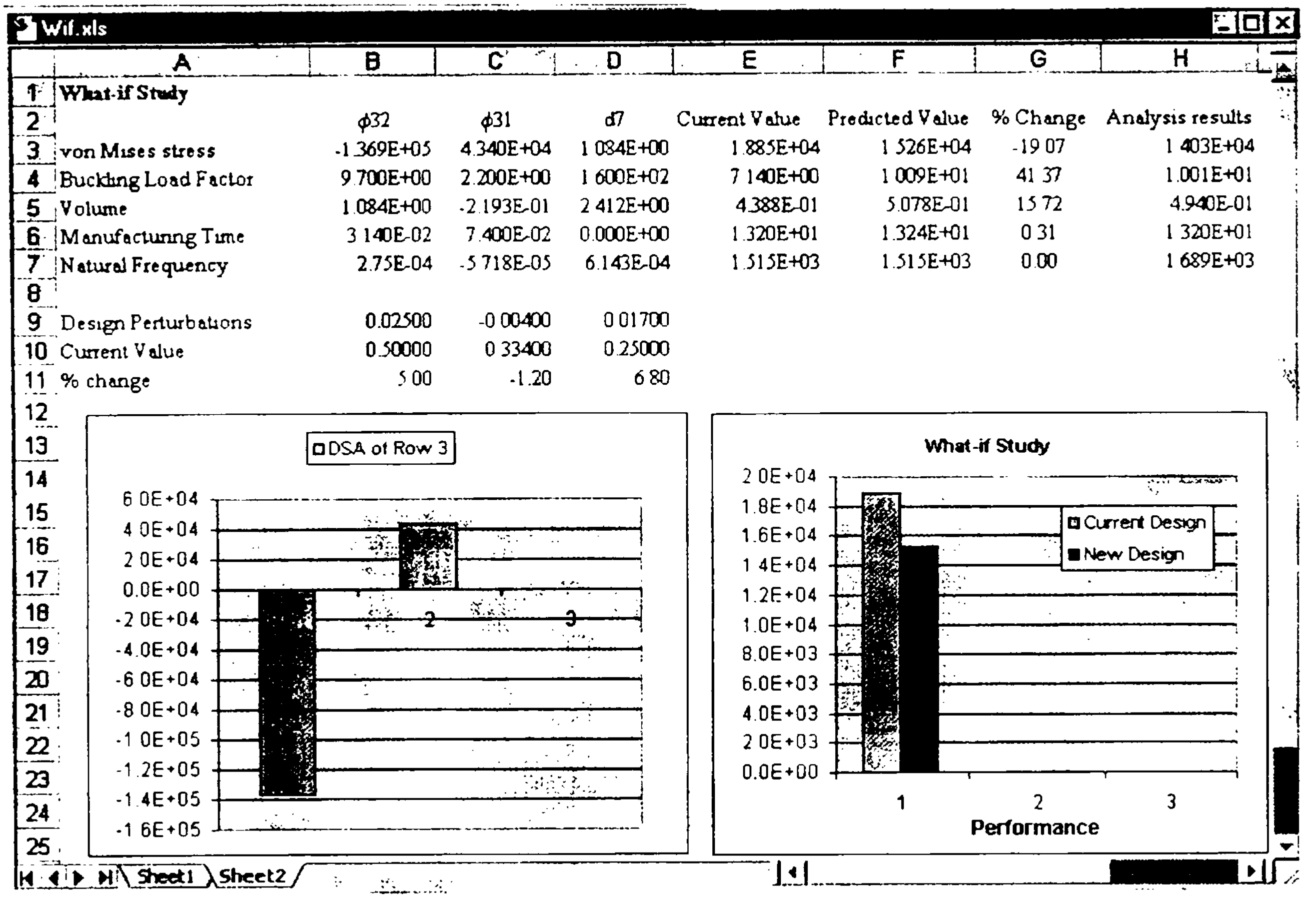
With sensitivity information, parametric study and design trade-off can be conducted for design improvements at concept and detailed design stages, respectively.

3.6.3 PARAMETRIC STUDY

A parametric study that perturbs design variables in the product design model to explore various design alternatives can support product concept designs effectively. The parametric study is simple and easy to perform as long as the mapping between CAD and simulation models are established. The mapping supports a fast simulation model generation for analyses. It also supports DSA using finite difference method. The parametric study is possible for the concept design since the number of design variables to perturb is usually small. Spreadsheet with proper formula defined among cells is well suitable to support the parametric study, for example, using Microsoft Excel, as illustrated in Figure 10.

3.6.4 DESIGN TRADE-OFF

The design trade-off method presented in this paper assists the design engineer in finding the most appropriate search direction for the design problem formulated in Equations (4). Four options are available in determining a design direction: (1) reduce cost (objective), (2) correct constraint neglecting cost, (3) correct constraint with a constant cost, and (4) correct constraint with a cost increment [33]. As a general rule of thumb, the first option, reduce cost, can be chosen when the



	A	B	C	D	E	F	G	H
1	What-if Study							
2		ϕ32	ϕ31	d7	Current Value	Predicted Value	% Change	Analysis results
3	von Mises stress	-1 369E+05	4 340E+04	1 084E+00	1 885E+04	1 526E+04	-19 07	1 403E+04
4	Buckling Load Factor	9 700E+00	2 200E+00	1 600E+02	7 140E+00	1 009E+01	41 37	1.001E+01
5	Volume	1 084E+00	-2 193E-01	2 412E+00	4 388E-01	5 078E-01	15 72	4 940E-01
6	Manufacturing Time	3 140E-02	7 400E-02	0 000E+00	1 320E+01	1 324E+01	0 31	1 320E+01
7	Natural Frequency	2 75E-04	-5 718E-05	6 143E-04	1 515E+03	1 515E+03	0 00	1 689E+03
8								
9	Design Perturbations	0.02500	-0 00400	0 01700				
10	Current Value	0.50000	0 33400	0 25000				
11	% change	5 00	-1 20	6 80				

Figure 10. Spreadsheet for parametric study and design trade-off.

design is feasible, i.e., all constraint functions are within the desired limits. When the design is infeasible, among the other three options, generally one may start with the third, correct constraint with a constant cost. If the design remains infeasible, the fourth option, correct constraint with a cost increment of, say 10%, may be chosen. If a feasible design is still not found, the second option, correct constraint neglecting cost, can be selected. A quadratic programming (QP) subproblem can be formulated to find the search direction numerically corresponding to the option selected. Details can be found in Reference [34].

3.6.5 WHAT-IF STUDY

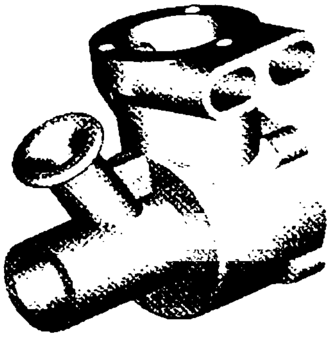
After the search direction $\boldsymbol{d}$ is found, a number of step sizes α can be used to perturb the design. Objective and constraint function values, represented as ψ_i, at a perturbed design $\boldsymbol{b} + \alpha\boldsymbol{d}$ can be approximated using the first-order sensitivity information of the functions by Taylor series expansion about the current design $\boldsymbol{b}$ without going through simulations, i.e.,

$$\psi_i(\boldsymbol{b} + \alpha\boldsymbol{d}) \approx \psi_i(\boldsymbol{b}) + \frac{\partial\psi_i}{\partial\boldsymbol{b}}\alpha\boldsymbol{d} \qquad (6)$$

Once a satisfactory design is identified after trying out different step sizes α in an approximation sense, the design model can be updated to the new design, and then simulations of the new design iteration can be conducted. Note that Equation (6) also supports parametric study, in which the design perturbation $\delta\boldsymbol{b}$ is determined by engineers based on the sensitivity information. In order to ensure a reasonably accurate function prediction using Equation (6), the step sizes must be small so that the perturbation $(\partial\psi_i/\partial\boldsymbol{b})(\alpha\boldsymbol{d})$ is, as a rule of thumb, less than 10% of the function value $\psi_i(\boldsymbol{b})$.

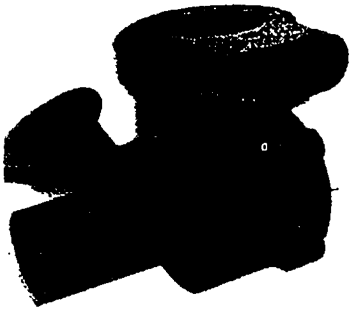
4. Rapid Prototyping

Rapid Prototyping, based on Solid Freeform Fabrication (SFF), is a newly developed manufacturing technology [36]. The SFF technology is an additive process that employs a layer building technique by inputting horizontal cross-section data from a 3-D CAD model. Beginning with the bottommost cross section of the CAD model, the Rapid Prototyping machine creates a thin layer of material by slicing the CAD model, into so-called 2 and 1/2-D layers. The system then creates an additional layer on top of the first, based on the next higher cross section. The process repeats itself until the part is completed. This process is illustrated using an engine case example shown in Figure 11. Rapid Prototyping systems are capable of creating parts with small



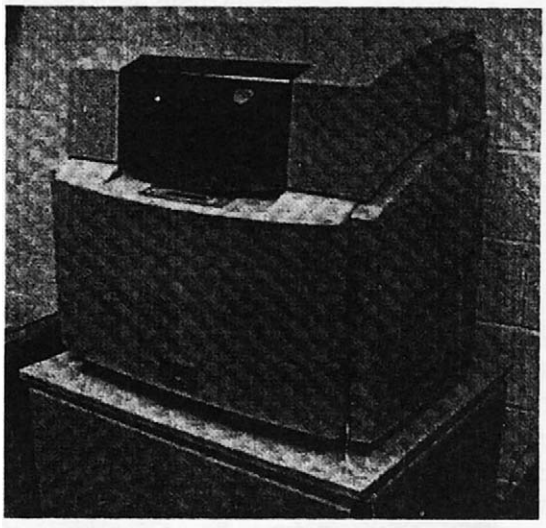
(a) 3-D CAD Model

(b) 2 1/2-D Slicing

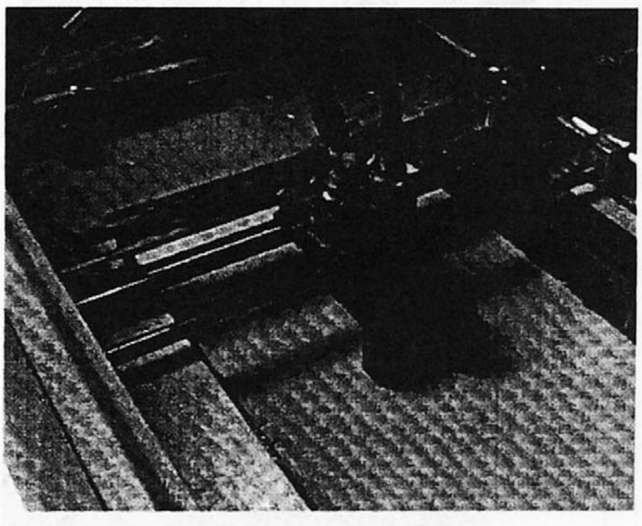


(c) Physical Model

Figure 11. SFF—layered manufacturing.



(a) Exterior of ModelMaker II



(b) Interior Work Room

Figure 12. SPI ModelMaker II system.

internal cavities and complex geometry. Most importantly, SFF follows the same layering process for any given 3-D CAD models. Therefore, it requires neither tooling nor manufacturing process planning for prototyping, as required by conventional manufacturing methods.

In the CDM environment, a ModelMaker II machine manufactured by Sanders Prototypes, Inc. [37], as shown in Figure 12(a), is employed. The ModelMaker II employs ink-jet technology. Plastic and wax materials are melted and dropped as build and support materials, respectively, on the substrate following the 2-D contours sliced from the 3-D solid model, as shown in Figure 12(b).

The physical prototypes are mainly for the cross-functional team to verify the product design and check the assembly. They can also be used for discussion with marketing personnel to trigger marketing ideas. In addition, the prototypes can be given to potential customers for feedback, therefore, bringing customers into the design loop in the early product development stage.

5. Example: Airplane Engine

A single-piston, two-stroke, spark-ignition airplane engine shown in Figure 5 is employed to illustrate the CDM paradigm and tool environment. The cross-functional team is asked to develop a new model of the engine with a 30% increment in both maximum torque and horsepower at 1,215 rpm. Design of the new engine will be carried out in two interrelated levels: system and component. At the system level, the performance measure will be the power output. At the component level, only design of the connecting rod will be presented.

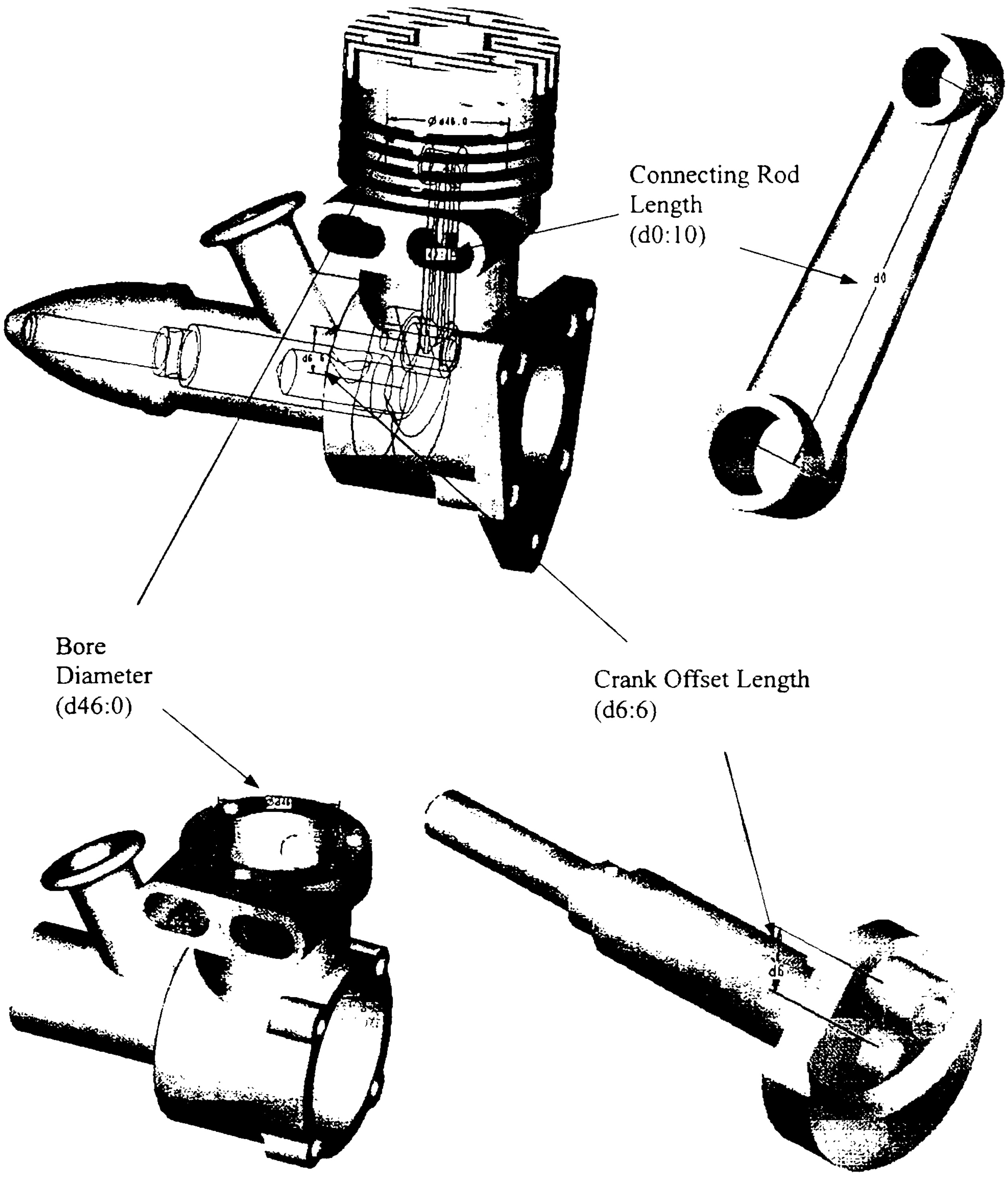


Figure 13. Engine assembly with design variables at system level.

Table 1. Changes of design variables at system level (unit: inch).

Design Variable	Current Value	New Value	Change	% Change
Bore diameter (d46:0)	1.416	1.6	0.164	11.6
Crank length (d6:6)	0.5833	0.72	0.1567	26.9
Connecting rod length (d0:10)	2.25	2.49	0.24	10.7

5.1 System Level Design

Power is proportional to the rotational speed of the crankshaft (N), the swept volume (V_s), and the brake mean effective pressure (P_b) [38], i.e.,

$$W_b = P_b V_s N \quad (7)$$

The effective pressure P_b applied on top of the piston depends, among other factors, on the swept volume and the rotational speed of the crankshaft. The pressure is limited by the integrity of the engine structure. Design variables at the system level include bore diameter (piston diameter d46:0) and the stroke, defined as the distance between the top edge of the piston at bottom and top dead center positions. In the CAD model, the stroke is defined as the sum of the crank offset length (d6:6) and the connecting rod length (d0:10), as shown in Figure 13. In order to achieve the system performance requirement, these three design variables are modified as listed in Table 1. The solid models of all the engine components are automatically updated and properly assembled via parametric relations established earlier [Figure 6(b)]. The change causes P_b to increase from 140 to 180 lbs., consequently, the peak load increases from 400 to 600 lbs. Therefore, load magnitude and path applied to the major load carrying components, such as connecting rod and crank

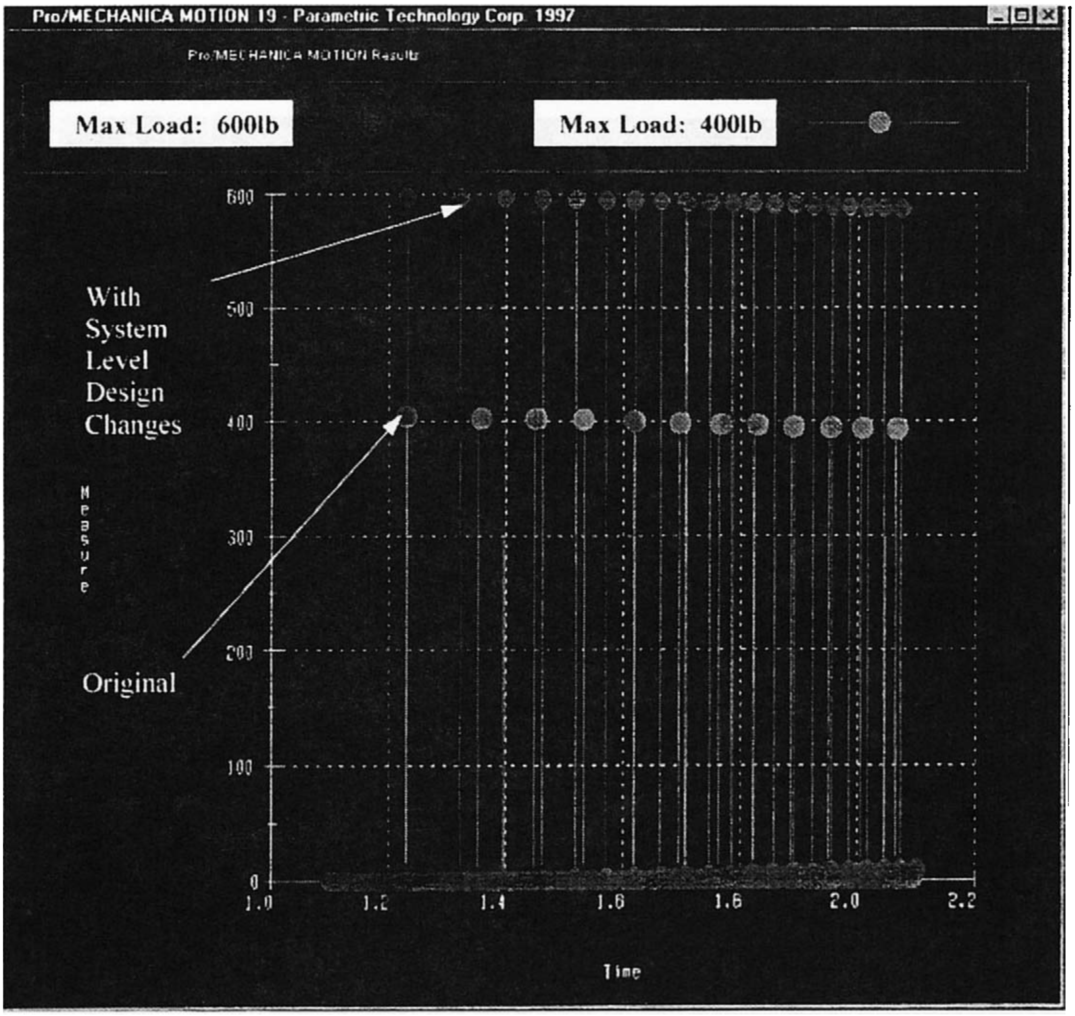
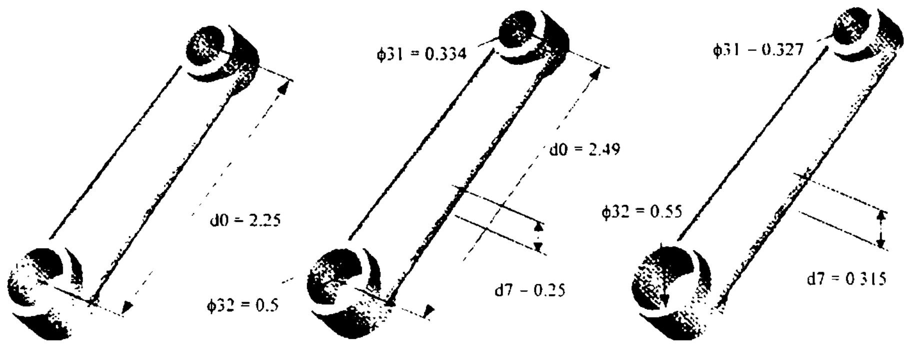


Figure 14. Dynamic load applied to the connecting rod.



(a) Original Design (b) Changes at System Level (c) Changes at Component Level

Figure 15. Engine connecting rod.

shaft, are altered. Motion analysis is conducted. Results show that the system performs well kinematically. Reaction forces applied to the major load carrying components are computed, for example, for the connecting rod shown in Figure 14. The change also affects manufacturing time for some of the components.

5.2 Component Level Design

Structural performance of the engine components is evaluated and redesigned to meet the requirements. In addition, virtual manufacturing is conducted for components with significant design changes. Build materials (volume) and manufacturing times constitute a significant portion of the product cost. In this paper, design of connecting rod will be presented to demonstrate the design decision making method discussed.

Due to the increased load transmitted through the piston and increased stroke length, the connecting rod could experience buckling failure during the combustion. In addition, due to change of stroke length, stiffness and mass will vary, hence the natural frequency of the rod may be different. Moreover,

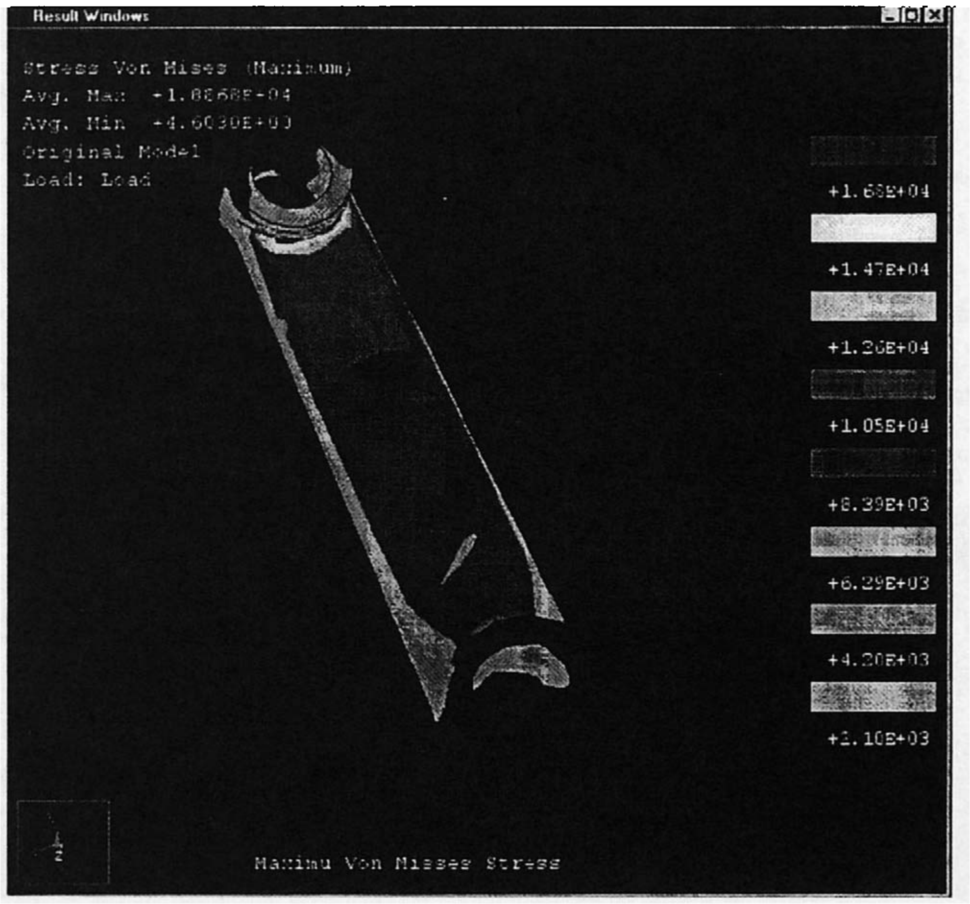


Figure 16. Stress distribution in the connecting rod.

Table 2. Changes of design variables at the component level (unit: inch).

Design Variable	Current Value	New Value	Change
Diameter of the big hole (ϕ32)	0.50	0.55	10%
Diameter of the small hole (ϕ31)	0.334	0.32728	−2.01%
Thickness (d7)	0.25	0.31484	25.9%

Table 3. Changes of performance measures at the component level.

Performance Measure	Current Value	New Value	Change
VM stress	18.9 ksi	10.5 ksi	−44.4%
Buckling LF	7.1	14.2	100%
Volume	0.438813 in^3	0.5488 in^3	25.1%
Machining time	13.2 minutes	13.2 minutes	0%
Natural frequency	1515 Hz	1840 Hz	21.5%

load is repeatedly applied to the connecting rod potentially leading to fatigue failure. Structural FEA and high cycle fatigue (HCF) are conducted to evaluate the performance. In addition, virtual manufacturing is carried out for machining cost of the rod.

Due to an increment of the connecting rod length (d0:10) shown in Figure 15, maximum von Mises stress of the connecting rod increases from 13,600 to 18,850 psi (Figure 16), and buckling loading factor decreases from 33 to 7. The first natural frequency is 1,515 Hz. The fatigue life is 10^5 cycles, and the machining time estimated for the connecting rod is 13.2 minutes using hole drilling and face milling operations, as shown in Figure 9.

5.3 Design Trade-off

The design trade-off method discussed in Section 3.5 is applied to the components with significant changes due to the system level design. Only the design trade-off conducted for the connecting rod will be discussed.

Performance measures of the connecting rod, including buckling load factor, fatigue life, natural frequency, volume, and machining cost, are brought together for design trade-off. Three design variables, ϕ32, ϕ31, and d7, are identified, as shown in Figure 15(b). The objective is to minimize volume and manufacturing time subject to the maximum allowable von Mises stress, the operating frequency, and the minimum allowable buckling load factor. The engine is designed to work at 21 Hz, and the minimum allowable buckling load factor for the connecting rod is assumed 10. The endurance limit is 12,000 psi after incorporating geometric and load correction factors [39].

Sensitivity coefficients of the performance and cost measures with respect to the design variables are calculated, as shown in Figure 10, using finite difference method. Design trade-off is conducted, followed by a what-if study. When a satisfactory design is found, the solid model of the rod is updated for performance evaluation and virtual manufacturing at the new design. This process is repeated twice when all the requirements are met. The design change is summarized in Tables 2 and 3. It is shown in these tables that the machining time is maintained and a small volume increment is needed to achieve the required performance.

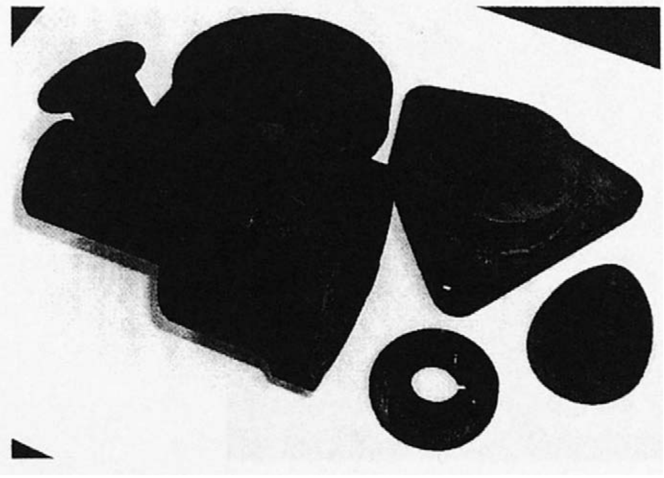


Figure 17. Physical prototypes of the engine parts.

5.4 Rapid Prototyping

When the design is finalized through Virtual Prototyping, ModelMaker II is used to fabricate a physical prototype of the engine, as shown in Figure 17. The prototype can be used for design verification as well as tolerance and assembly checking.

6. Conclusions and Future Work

In this paper, a concurrent design and manufacturing paradigm and a CDM software tool environment have been presented. The proposed CDM paradigm employs Virtual Prototyping for product design and Rapid Prototyping for fabricating physical prototypes of the design. The CDM paradigm presents three unique features. First, the proposed CDM employs Virtual Prototyping technique to simulate product performance, reliability, and manufacturing cost, and brings these measures for design. Second, it employs a systematic and quantitative method for design decision making for the parameterized product in solid model forms. Third, the method integrates a Rapid Prototyping tool for fabricating prototypes of the design that brings marketing personnel and potential customers into the design loop.

With intensive simulations and advancements in simulation technology, requirements of hardware prototypes and field tests that are traditionally used to identify product performance and reliability can be minimized. In addition, manufacturing related issues can be largely addressed through virtual manufacturing in early design stages. Moreover, manufacturing process planning conducted in the virtual manufacturing streamlines the production process.

Currently, more modeling and simulation tools are being investigated to support a broader class of engineering problems. A CDM testbed is being established at the Concurrent Design and Manufacturing Research Laboratory to allow industry to exercise the CDM paradigm. In the long run, the CDM environment must be tailored and planted into company's design environment. Currently, several mid-size companies, such as York International, Seagate Technology, and Halliburton Energy Services, have been approached for possible implementation of the CDM paradigm and environment. A lot more work needs to be done to bring successful stories to the design community.

Nomenclature

ψ: product performance measure

ψ^u: upper bound (requirement) of the product performance

P_f: probability of failure
P_f^u: upper bound (requirement) of the probability of failure
C: objective (cost) function to be minimized
$\mathbf{b}$: vector of design variables
b_k^l and b_k^u: lower and upper bounds of the design variable b_k
Δb_k: design perturbation of the kth design variable
$\psi(X)$: performance measure defined as a failure event
$\mathbf{X}$: vector of random variables
$f_X(x)$: joint probability density function of the random variables $\mathbf{X}$
$P[\bullet]$: probability of event •
$\mathbf{d}$: search direction to be determined in design trade-off
α: step size along the search direction
W_b: engine power and torque
P_b: engine brake mean effective pressure
V_s: swept volume of an engine
N: rotation speed of the engine crankshaft

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