The rapid tooling testbed: a distributed design-for-manufacturing system

David W. Rosen
Yong Chen
Shiva Sambu
Janet K. Allen and
Farrokh Mistree

The authors

David W. Rosen, Janet K. Allen and **Farrokh Mistree** are Associate Professor, Senior Research Scientist, and Professor, respectively, in the School of Mechanical Engineering, Georgia Institute of Technology, Atlanta, Georgia, USA.
Yong Chen is a Software Engineer at 3D Systems, Valencia, California, USA.
Shiva Sambu is a Manufacturing Engineer at Align Technology, Santa Clara, California, USA.

Keywords

Rapid prototyping, Rapid tooling, Stereolithography

Abstract

A new design-for-manufacturing method, called the geometric tailoring (GT), and the associated digital interface concept have been developed that enable the design activities to be separated from the manufacturing activities. Conditions for the successful application of this method are investigated. The GT method is demonstrated for rapid prototyping and rapid tooling technologies, where prototype parts are required to match the production properties as closely as possible. This method is embodied in a system called the rapid tooling testbed (RTTB). Research work is presented on GT and the distributed computing environment underlying the RTTB. Examples are summarized from the usage of this method and testbed.

Electronic access

The Emerald Research Register for this journal is available at
http://www.emeraldinsight.com/researchregister

The current issue and full text archive of this journal is available at
http://www.emeraldinsight.com/1355-2546.htm

Rapid Prototyping Journal
Volume 9 · Number 3 · 2003 · pp. 122–132
© MCB UP Limited · ISSN 1355-2546
DOI 10.1108/13552540310477427

Introduction

One tenet of concurrent engineering and design-for-manufacturing (DFM) is the need for an early involvement of manufacturing and other groups in product development projects. In apparent violation of this tenet, there is a push within the rapid prototyping (RP) community to separate the design and manufacturing activities. It is a common practice to create CAD models and STL files, ftp them to service bureaus, and receive physical parts within days. RP technologies (such as stereolithography (SLA) and selective laser sintering) enable this separation between design and manufacturing activities by virtue of their capability to fabricate complex shapes directly from a CAD or STL model.

In the mid-1990s, the US National Science Foundation created the *distributed design* and *fabrication initiative* to investigate the separation of design and manufacturing activities in the context of RP technologies. The hypothesis was that a standard interchange format for RP processes can be developed that enables design activity to be separated from the manufacturing activity, and that little additional communication between these activities is necessary. Under this initiative, a rapid tooling testbed (RTTB) was developed to investigate this hypothesis. We created the technological infrastructure for RP, rapid tooling (using RP to fabricate injection molds), and distributed product realization. The key question that we addressed was: *How early in the product realization process, and under what conditions, can the design be separated safely from manufacture?*

The problem defined by the research question can be restated more informally as "who is responsible for the DFM?" DFM is often difficult for mechanical parts, since significant manufacturing knowledge is required to adjust the part designs to aid manufacturability by a specific process. However, if the manufacturer understands the purpose of a design and its functional

---

We gratefully acknowledge the support from the US National Science Foundation, grant DMI-9618039, and the RPMI industry members at Georgia Tech.
Received: 31 August 2002
Reviewed: 10 December 2002
Accepted: 28 February 2003

requirements, then he/she can adjust the design to facilitate manufacturing without compromising functionality.

The overall context for the RTTB is shown in Figure 1. The three main stages in the product realization process of relevance to this project include functional design, design-for-manufacture, and manufacturing (tooling and fabrication). Design involvement is separated from manufacturing involvement, but the software tools and information formats for the design and manufacturing organizations overlap. The key question of the project relates to the timing of the transfer from design to manufacturing and the scope of the DFM stage.

Overall, our approach to answer the key question was to experiment with different timings of design-to-manufacture transfer and by scoping the DFM tasks differently. We separated the design and manufacturing activities in such a way that the designer transfers as much information as possible about the design, its requirements, and design freedom, and then allow the manufacturer to perform DFM, process planning (PP), and manufacturing. Design freedom refers to the design's attributes that the manufacturer can adjust, and the ranges of the adjustments, in order to perform DFM.

The digital interface between the designer and the manufacturer denotes the information package that was transferred to the manufacturer (Fernandez *et al.*, 2002). We experimented with STL files, CAD models, and design decision formulations with integrated CAD and FEA models as the digital interface.

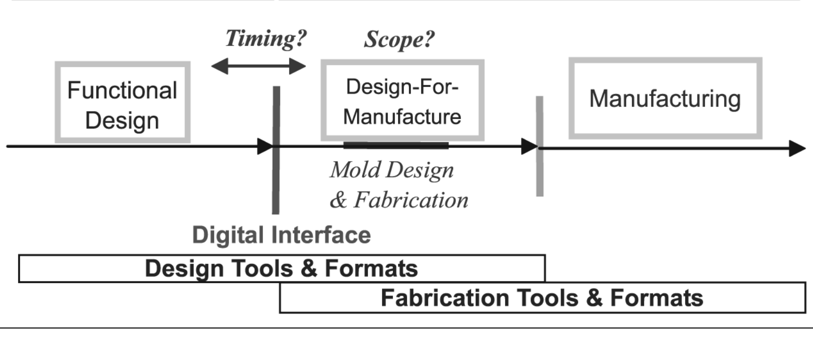
In the next section, we present our DFM method called "geometric tailoring" (GT). In Section 3, the RTTB system is presented, as well as the distributed computing environment on which it is based. Section 4 is devoted to the experiments used to test the GT DFM method and the RTTB system. Finally, conclusions are drawn from our experiences.

GT DFM method

Problem statement and approach

The purpose of DFM is to ensure that parts can be manufactured to meet their requirements in the most cost- and time-effective manner. To accomplish this, it is often necessary to modify the part designs to facilitate the selected manufacturing process in a better way. This is, especially, true when building prototypes that are to be the representative of production parts. For example, a prototype gear train is to be fabricated in a different material and with a different process than the production gear train. Further, assume that the prototype gear train undergoes a functional testing with a concern on its gear tooth stress. Then, gear dimensions must be modified so that the prototype gear teeth have the same stress characteristics as the production gear teeth under similar operating conditions. The process of modifying prototype parts' dimensions is called GT. For the most part, it is necessary to compensate for differences in the material properties (between production and prototype materials) when fabricating prototype parts in RP technologies. The situation is more complicated in injection molding prototype parts, since there are two manufacturing processes to be considered: the process to fabricate the mold, and the molding process itself. Both processes must be considered when performing the GT.

Figure 1 RTTB process and digital interface



Given this introduction, the GT DFM problem can be stated as:

> *Given a part design, functional requirements, design freedom, and time and cost targets for a set of prototype parts, compensate for differences in mechanical properties of prototype materials and production materials by modifying the part geometry, designing a mold, and designing mold fabrication and injection molding processes.*

Consider that a functional prototype is needed to test a property of the production part. Using the concepts from similitude (e.g. Buckingham Π theorem), the "property of interest", X, for a prototype part and a production part can be formulated as a function of a set of part dimensions (Cho *et al.*, 1999). Part dimensions can be divided into two categories based on their effect on X. Assume that dimensions $d_1, d_2, \ldots, d_k$ have a significant effect on X, while dimensions $d_{k+1}, d_{k+2}, \ldots, d_n$ have a minor effect. The principle of the approach developed in this research is to change the model (prototype) dimensions $d_{m,j}$ (for $k+1 \leq j \leq n$), such that $d_{m,i}$ (for $1 \leq i \leq k$) match as closely as possible the production dimensions $d_{p,i}$ ($1 \leq i \leq k$) based on the design and process goals and constraints. These dimensional changes are referred to as GT. Continuing the gear example, the face width and diametric pitch dimensions would have a significant effect on the gear tooth stress, while the diameter of the hole for the shaft would have a negligible effect.

GT problem formulation

For RP-produced prototype parts, the problem formulations are called material-process geometric tailoring (MPGT)/RP. These problems are the result of combining a problem that captures functional requirements and a problem that captures manufacturing and material capability. Problem formulations are based on the compromise decision support problem (DSP) formulation (Chen, 2001; Sambu, 2001), which is an extension of goal programming formulations. Compromise DSP formulation model decisions, in which, typically, multiple conflicting goals must be met as much as possible, while satisfying a set of constraints (Mistree *et al.*, 1993). A set of system variables may be adjusted in order to meet these goals. The MPGT problem formulation template is shown in Figure 2.

In the MPGT formulations, the system variables, goals, and constraints can be specified by the designer or the manufacturer. Designer specified information includes a parametric CAD model of the part, constraints and goals on functional, geometry, cost and time characteristics, analysis models for these constraints and goals, target values of goals, and preferences for the goals. Although, the designer has a preferred value for the design variables, he/she specifies a feasible range (instead of a point) for these variables. The manufacturer provides process variables, RP and production material properties, process constraints and goals, and analysis models. Note that process goals do not affect any of the designer's goals in the GT problem. Also, cost and time goals are affected only by the manufacturing process. However, the designer specifies the targets for these goals to ensure that the part meets its design specifications. The listing of these target values in the GT problem serves the purpose of transferring these requirements to the manufacturing group.

To formulate a DFM problem, the designer fills in the MPGT template with the information described earlier. This incomplete MPGT formulation is then sent to the manufacturer, who fills in the remaining information. With the completed formulation, the manufacturer is now able to solve the DFM problem, performing GT of the part design. Hence, the MPGT serves as the digital interface between the designer and the manufacturer.

The system variables in the problem are the part dimensions that the designer has identified as having a minor effect on functionality and which are modifiable by the manufacturer. These variables can be modified within the range specified by the designer to obtain better functional properties. Deviation variables correspond to the deviation of goal achievements. Each goal has two deviation variables (corresponding to under and over achievement). Bounds for the system variables are obtained by the physical limitations on geometry variables. The deviation function is a linear physical programming form of the Archimedean formulation of deviation variables (Hernandez *et al.*, 2001).

It should be noted that considerable coupling usually occurs between the design and manufacturing goals, such as the cost, surface finish, stress or displacement goals, since they are typically the functions of both

Figure 2 Materials process GT problem formulation

GIVEN:	
• Parametric CAD model of design	• Material Properties
• Target values for variables	• Process Properties
• Target value for goals, G_i	• Goal preferences as weights, W_i
FIND:	
System Variables:	**Deviation Variables**:
CAD model parameters:	deviation of goals from targets
$X = \{x_j \mid j = 1,\ldots,m\}$	$d_i^-, d_i^+, i = 1\ldots n$
Mfg. Process variables:	
$X = \{x_j \mid j = m+1,\ldots,q\}$	
SATISFY:	
Goals:	**Constraints**:
Meet targets for design goals:	(none built into template)
$A_d(X) + d_i^- - d_i^+ = G_i$	
Meet targets for process goals:	
$A_m(X) + d_i^- - d_i^+ = G_i$	
MINIMIZE:	
Deviation Function: Weighted sum of Goal Deviations:	
$Z = \Sigma\, W_i \cdot d_i^*$	

design and manufacturing variables. For example, geometry variables modify part size and hence, affect the build time and part cost. Surface finish can be a coupled goal under two circumstances. Firstly, varying geometry variables affects the orientation of surfaces in the part and hence affects surface finish, and secondly varying geometry variables varies the best part orientation and hence affects the surface orientation and surface finish. Coupled goals complicate the solution process.

MPGT for rapid tooling. For the case where the prototype parts are injection molded, additional considerations especially, the variation of molded material properties must be included. The material and mechanical properties of SL molded parts can be different from those of production parts (Dawson, 2001). For example, tensile modulus and strength of parts molded in SL are typically lower than the parts molded in steel, while flexural properties are enhanced. These mechanical property differences cause prototype parts to have different behaviors than production parts in their intended in-use situations. The MPGT/RT problem compensates for these mechanical property differences. It combines three problems: one for functional design, one for SL fabrication process design of the molds, and one for the design of the molding process.

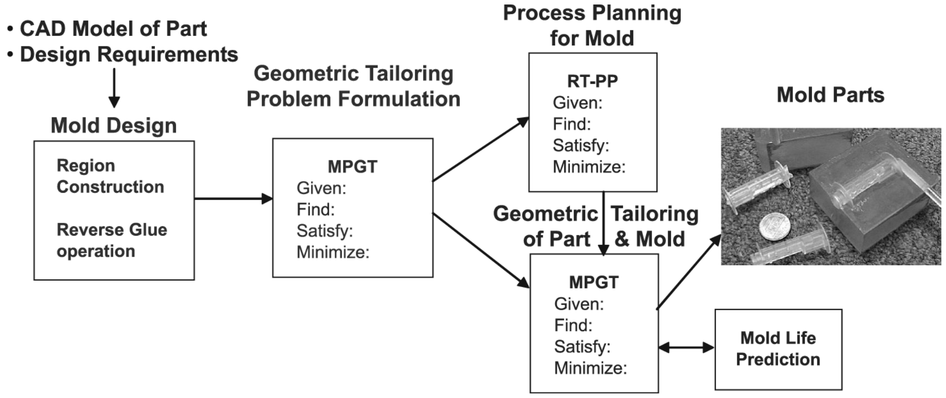
Solution procedure

The solution procedure is based on the robust concept exploration method (Chen *et al.*, 1997). The solution approach is to decompose the MPGT problem into smaller sub problems, nominally design and manufacture, that are simpler to solve, and to decouple these sub problems to the extent possible. Then, the manufacturing problem is solved first for various values of design variables. Design of experiments (DOE) methods are used to specify the design variable sampling strategy. After the approximation models of process capabilities are developed, the design sub problem is solved using these approximation models. When a rapid tooling problem is being solved, two manufacturing sub problems are developed, one for RP-PP of the mold and one for the injection molding process. The sequence of steps is shown schematically in Figure 3, where only one manufacturing sub problem (rapid tooling process planning (RT-PP)) is shown for simplicity.

Decoupling of the sub problems is attempted by rearranging the goals and constraints that are the functions of only design or manufacturing variables. Surface finish is an example of a design goal that is a function of manufacturing variables only; finish goals are moved to the decomposed manufacture sub problem.

DOE and response surface methodology techniques (Myers and Montgomery, 1995) are utilized for two purposes in this work. Evaluation of goals and constraints often require time consuming analysis, such as finite element analysis. Rather than embed FEA in an optimization loop, surrogate (approximate) models of the part's functional behaviors are computed. Additionally, SL-PP can require substantial computing times due

Figure 3 Work flow of SL rapid tooling process



to the need for the adaptive slicing of CAD models of parts or molds. As a result, surrogate models of manufacturability for different part dimension values are built to further decouple the problem.

The results obtained from the Modified RT-PP problem are used to solve the modified MPGT/RT problem. As mentioned, the modified RT-PP results are used to build surrogate models of process capability for various settings of part design parameters. The modified MPGT/RT problem is solved for each solution obtained from the modified RT-PP problem and a selection (based on the objective function value) is performed to determine the best of the obtained solutions. OptdesX with a simulated annealing (SAN) algorithm is used to solve the problem. The calculation of surrogate models, deviation variables and objective function are performed in C++ code integrated with OptdesX.

Web-based distributed product realization environment

A distributed computing environment is essential for the implementation, testing, and deployment of the RTTB. Research efforts were focused on two major aspects: one is the development of a suitable computing framework, and the other is modelling the information that flows through the framework to enable design and fabrication. Three versions of distributed computing environments were developed, along with three methods of information modelling.

The third computing framework was called web-DPR, a web-based distributed product realization environment (Xiao *et al.*, 2001). Web-DPR enabled users to interact with product models, perform GT, and explore the effects of changes in project requirements through web browsers. Communications between agents in web-DPR occurred using the events that were broadcast through event channels. However, instead of encapsulating message, control, and information within an event, events contained only message/control information, while application content was routed through a separate data flow. Message information was encoded using XML. Interoperability of distributed objects was accomplished using Java-RMI. The web-DPR framework is shown in Figure 4. Note the separation of message flows (through event channels) and data flows (through the data vault).

The RTTB system was implemented on the web-DPR framework. A set of general and RTTB-specific agents were integrated using two event channels, one for design activities and one for manufacturing activities. The manufacturing event channel, shown in Figure 5, will be described further, since it is relevant to this presented paper. An incomplete MPGT problem formulation is the input into the manufacturing event channel, as described in the previous section. The event channel's agents are presented later.

The "process and material selection agent" (not shown) was implemented by extending the selection decision support problem (DSP) (Mistree *et al.*, 1993). The essence of the selection DSP is to rate a set of alternatives against a set of attributes, then rank-order the alternatives. In this work, the alternatives are candidate materials and fabrication

Figure 4 Web-DPR framework

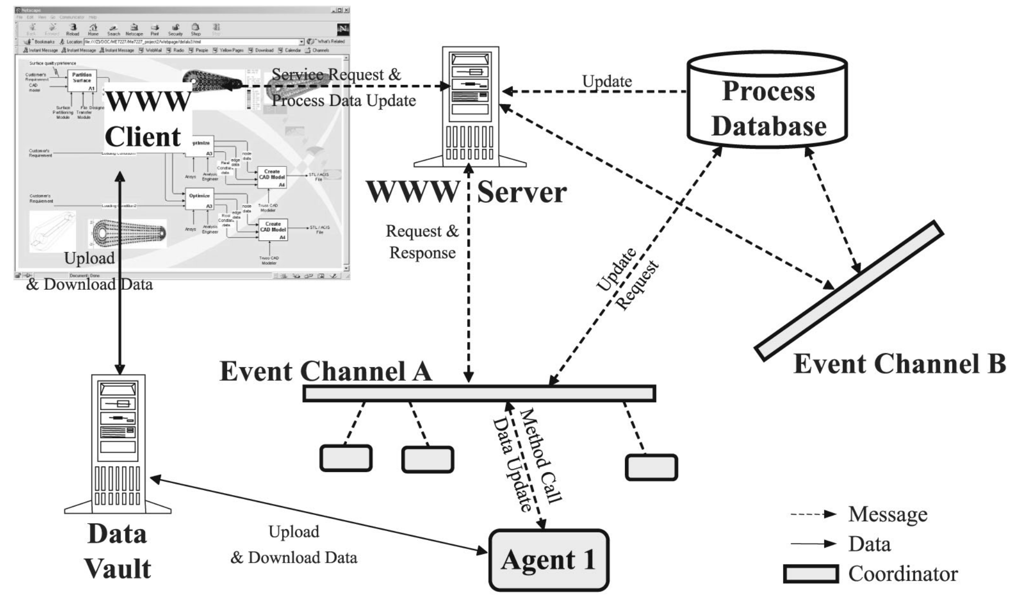
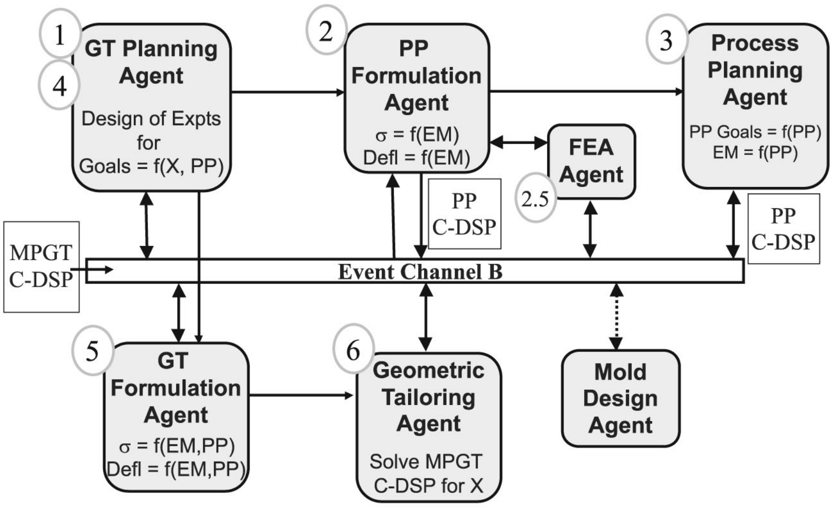


Figure 5 RTTB system architecture



processes, while the attributes are derived from product requirements. A utility-based selection decision support problem (U-sDSP) formulation and solution method were developed and tested as part of this project (Fernández *et al.*, 2001; Rosen and Gibson, 2002).

After selecting the appropriate materials and processes, DFM activities are typically performed. We developed GT methods for both part designs and mold designs. To support GT, we developed SL PP capabilities. Also, limited injection molding process design was also accomplished. The GT planning agent designs the set of experiments from which surrogate models of process capability will be developed. After PP is performed, this agent builds response surfaces and forwards them to the GT formulation agent.

After a part or mold is designed, it is necessary to design the fabrication process to be utilized to make the part or mold. Our approach is to develop experimental and analytical models that relate process variables to measures of part quality. Two agents were developed to support this work. The process planning (PP) formulation agent takes the material-process GT formulation and formulates the SL PP problem. The compromise DSP was used as the problem formulation. Appropriate PP constraints and goals are derived from the GT formulation. This agent supports a high level of user interaction in order to perform problem formulation.

The third agent, PP agent, solves the formulated PP problem. Based on the experimental work, fabrication process design methods were developed that enable the selection of appropriate process variable values to achieve to build goals of accuracy, surface finish, and build time. We developed a PP strategy that consists of three stages:

(1) orientation,
(2) slicing, and
(3) parameterization.

Trade-offs among build time, accuracy, and finish are made in each stage so that only the most appropriate process plans are passed to the next stage. Three generations of SL process design software tools were developed (Lynn-Charney and Rosen, 2000; West *et al.*, 2001). The latter two versions incorporated a new adaptive slicing algorithm.

Given that the input to the RTTB will be a part or product design, it must be possible to design a mold for the part(s) that can be fabricated using RP techniques. The mold design agent accomplishes this. As implemented, this agent is a stand-alone program that is only loosely integrated into the RTTB (hence, the dotted lines connecting it to the event channel in Figure 5). We developed a library of mold insert CAD models (ProEngineer, SolidWorks) with suitable mounting and ejection holes, gate, runner, and sprue features. After fabrication, the inserts fit into standard mold bases for injection molding parts. The types of rapid tools (molds) that we have studied include solid SL inserts, SL shelled inserts that are backfilled with epoxy or low-melting-point metals, and epoxy inserts that are cast into rapid prototyped dies.

We developed a new method of automated mold design that was suitable for simple two-piece molds, consisting of core and cavity, as well as molds with many additional moving sections (Chen and Rosen, 2002a). Our approach utilizes planar parting surfaces, which tend to result in better molded parts than would be produced if curved parting surfaces were used with rapid tooling materials. These methods and algorithms are reported by Chen and Rosen (2002b).

The final two agents (GT formulation and GT) enable the formulation and solution of the integrated GT problems. The GT formulation agent enables the user to manually formulate the problem. The GT agent is implemented as a wrapper around OptdesX.

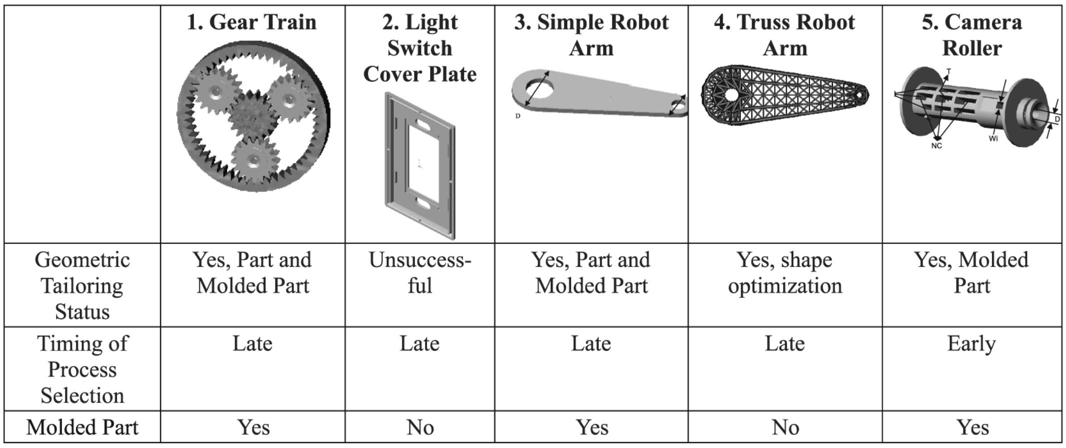
Experiments and results

We conducted GT experiments with many parts, five of which are summarized in Figure 6. GT was performed on all part designs; GT for rapid tooling was performed on three of the parts. Process selection, early vs late, indicates the extent of design changes that the manufacturer could perform. For GT purposes, we assumed that parts would be fabricated on a SLA-3500 machine in CibaTool SL7510 resin. Molded parts would be produced using SL tools in polystyrene.

Experiment specifics (variables and goals) are shown in Table I, along with GT results. It should be noted that in the goal formulations, target values represent ideal cases that are not always expected to be achievable. Goals values are provided at ideal, desirable, acceptable, tolerable, and unacceptable levels, according to the linear physical programming formulation method (Hernandez *et al.*, 2001). Constraints are automatically added to the problem formulation that prevent goal achievements at an unacceptable level. For four of those parts, GT worked very well, as it was possible to improve the performance characteristics of prototype parts relative to the production parts' designs. In the fifth case, enough design freedom was not available to enable a significant change in the part performance. Each problem will be described briefly.

For the gear train problem, the ring gear was subjected to GT. Three design variables were included: face width (W), diametric pitch (P), and number of teeth (N). A maximum tooth stress goal was formulated. The target value for stress was adjusted to compensate for the mechanical property differences between injection molded ABS and SL-7510 SLA resin. GT of the ring gear was successful. A MPGT/RT problem was also formulated and solved. Ring gears were injection molded and tested successfully for functionality.

Figure 6 Major examples and experiments



	1. Gear Train	2. Light Switch Cover Plate	3. Simple Robot Arm	4. Truss Robot Arm	5. Camera Roller
Geometric Tailoring Status	Yes, Part and Molded Part	Unsuccessful	Yes, Part and Molded Part	Yes, shape optimization	Yes, Molded Part
Timing of Process Selection	Late	Late	Late	Late	Early
Molded Part	Yes	No	Yes	No	Yes

Table I Results of major experiments

	Design Variables			Manufacturing Variables			Goals		
Experiment	**Name**	**Range**	**Solution**	**Name**	**Range**	**Solution**	**Name**	**Target**	**Solution**
Gear Train (RP)	*W* (mm)	2.5-10.2	5.72	–			Tooth Stress (MPa)	28.8	28.66
	P (t/mm)	1.54-1.81	1.57						
	N (-)	51-57	55						
Light Switch (RP)	*A* (mm)	0.5-2.5	1.20	LT (mm)	0.051-0.2	0.2	Force (N)	2.94	2.95
	T (mm)	2.5-5.5	2.5	HOC (μm)	25-178	67	Deflect (mm)	5	4.68
				FOC (μm)	51-406	51	Volume (mm^3)	24054	24129
							Time (hr)	40	24.6
							Cost ($)	2000	2500
							SF (μm)	5	6
Simple Robot Arm (RT)	*D* (mm)	15.24-25.4	20.68	Draft (°)	0-5	0.61	Stress (MPa)	5.99	5.99
	d (mm)	7.62-12.7	9.92	HOC (μm)	51-203	25-51	Y Disp. (mm)	0.51	0.49
	t (mm)	2.54-3.56	2.99	FOC (μm)	51-406	51-306	Weight (g)	3.4	3.36
				Cool Time (s)	300-420	300	SF (μm)	0.5	1.6, 1.6
							SF PP (μm)	0.25	0.2,0.2
							Tols (μm) (4)	51, 25	51, 51
							Cost ($)	150	570
Truss Robot Arm (RP)	*D*1-*D*8 (mm)	1-5	1.75	–			Weight (g)	40	55.3
			4.52				Deflection (mm)	0.06	0.0603
			4.72						
			3.6						
			3.46						
			3.18						
			3.98						
			2.34						
Camera Roller (RT)	*D* (mm)	2.75-4.75	2.78	Draft (°)	0-5	1.3,1.2,1.0	Z Rot (rad)	0.0131	0.0104
	W$_i$ (mm)	2-4	2.80				Weight (g)	2.28	2.40
	t (mm)	1-3	1.00	HOC (μm)	51-203	51	SF (μm)	2	4, 4, 2
	NC (-)	2-3	2	FOC (μm)	51-406	306	SF PP (μm)	0.5	0.2, 2
	NR (-)	2-3	2	Cool Time (s)	300-420	300	Tols (μm)	25	46,51
							Tols (μm)	51	41,46
							Tols (μm)	76	163
							Cost ($)	500	1291

The light switch cover plate was less successful. Two design variables were included, the width (A), and thickness (T), of snap fits on the cover plate. Force, deflection, volume, time, cost, and surface finish goals were included. Layer thickness (LT), hatch over cure (HOC), and fill over cure (FOC) were the manufacturing variables. Despite providing fairly wide design variable ranges, the snap fits could not be adjusted enough to completely compensate for the mechanical property differences between ABS and SL-7510.

The third problem, the simple robot arm, worked very well for both the part and the rapid tooling GT. Three design variables were modelled, the outside diameters, D and d, of the arm ends and the arm thickness, t. The design problem is to have the arm deflect minimally, subject to a bending force that simulates dynamic loading. Stress, deflection, weight, surface finish, tolerances, and cost are the design goals. For the rapid tooling problem, additional manufacturing goals are added for the surface finish of the mold pieces and for mold life. Molds were fabricated on a SLA-3500 machine and 50 robot arm parts were molded in polystyrene. Several of these parts were tested and measured. Dimensions were accurate to within 0.5 percent. Tensile strength differed by 2.6 percent, while elastic modulus differed by 8.5 percent. Tolerances and surface finishes met or exceeded expectations. Altogether, we believe that this example successfully demonstrated that the GT method effectively compensates for material property differences between prototyping and production material.

For the fourth problem, the stress and deflection behavior of a robot arm filled with truss structure was investigated. Again, a bending load was applied to the arm. The design variables were eight groups of truss element diameters (D1 - D8). A maximum stress constraint value was computed by compensating for the flexural strength differences between a mild steel and SL-7510. The MPGT/RP problem was solved successfully, minimizing part weight while meeting the deflection target.

For the fifth problem, the rapid tooling problem will be presented. We simulated the early transfer of the problem from the designer to the manufacturer by allowing the manufacturer to modify the number and arrangement of features in addition to the sizes of features. In the camera roller, many small slots are used to minimize weight and facilitate injection molding, while providing enough stiffness. The number of rows and columns in the array of slots (NR, NC) were design variables. Additionally, other features could be added, removed or moved, but these cannot be described concisely by variables. The diameter of the hole in the roller end (D), a slot width (W_i), and rib thickness (t) were the other design variables. Given that film is wound onto the roller, a torsional loading condition was applied and an angular deflection goal (Z Rot) was formulated. Weight, surface finish, tolerances, and cost were the additional design goals. Surface finishes of mold pieces were the manufacturing goals. After solving the MPGT/RT problem, many goals were met; those that were not met were still well within the acceptable range.

Generalizing from these experiments, some summary comments can be made.

MPGT for RP. Most designs that were tested showed significant improvement in matching production-like performance characteristics. We could integrate the design and manufacturing models effectively by using the compromise DSP formulation. The integrated problem formulation was decoupled effectively into a RP PP-problem and a GT problem. DOE and response surface methods worked well in modelling the coupling between the problems. However, we found that the response surfaces did not always fit well into the design space, but the fit could be improved if the design space size was reduced. For the simple robot arm (experiment 3), a two-stage solution procedure was used. In the second stage, a smaller design space was formulated, based on the results of the first stage. A significant improvement in the prototype performance was achieved.

In one GT problem (experiment 2), significant improvements in prototype performance could not be achieved. This is because the design variables could not be modified without violating other design requirements. The conclusion here is that the GT success depends on providing the manufacturer with sufficient design freedom to enable some DFM.

MPGT for RT. The MPGT method for rapid tooling was applied to three parts, namely, one gear in the gear train, simple robot arm, and camera roller (experiments 1, 3, 5 in Figure 6). In these cases, the experiments were very successful. The injection molded robot arm parts were tested for their strength, stiffness, weight, surface finish, accuracy, and mold life. Strength and stiffness were improved while meeting most of the other requirements. Draft angle of the mold was modified in order to achieve the mold life objective.

For the camera roller, both GT and configuration design were performed by the manufacturer. That is, the number and arrangement of rib and slot features were modified, as were their dimensions. This indicates an early transfer from design to manufacturing, before the designer specified a lot of design details. Finite element analysis results showed an improvement in stress and deflection performance of molded parts.

Web-DPR. The framework efficiently delivers message and data to the appropriate agents. Details of the complex information communication activities are hidden from users. The separation of message and information flows is beneficial for two reasons. First, it enables the usage of a standard event class. Second, it greatly reduces network traffic, since data files are not routed through the main web server. The usage of standard events and the organization of agents onto multiple event channels simplified the development of the RTTB system. Additionally, web-DPR facilitated experimentation with various DFM processes, since it was straightforward to implement a sequence of messages that invoked appropriate behavior among agents to execute a DFM process.

The examples, experiments, and web-DPR are more completely presented in the references Chen (2001), Sambu (2001) and Xiao *et al.* (2001).

Conclusions

From our activities and experiments, we found the following.

- Communicating a part's nominal geometry was insufficient to enable the manufacturer to design the RP process plan to meet designer requirements. If only CAD or STL models are transferred, the designer must complete the part design, including DFM.
- By communicating additional design information, requirements, and preferences to the manufacturer, the designer enables the manufacturer to design a RP process plan to attempt to meet as many requirements as possible. With the designer's preferences among time, cost, accuracy, and surface finish, the manufacturer can meet the designer requirements in a better way by exploring trade-offs among various process plans.
- GT can be performed effectively, if the designer provides sufficient design freedom to the manufacturer, along with the information as described previously. Both GT for RP and RT are enabled. Hence, design can be separated safely from manufacturing if this information is communicated to the manufacturer and the manufacturer performs DFM. This effectively answers the key question asked in the introduction part of this paper.
- The concept of a digital interface appears to be a promising construction with which communication paths between organizations can be defined. This work demonstrated that selection and compromise decision templates can serve as the interchange format and can capture functional requirements, design freedom, tolerance and surface finish requirements, and project constraints (time and cost).
- Distributed design and fabrication requires a computing environment that enables participants to share information and collaborate. Results demonstrate that a web-based environment can effectively integrate distributed and heterogenous computing resources (hardware and software) for engineering design and manufacture using client/server architectures. Our web-DPR framework proved to be a flexible computing environment for developing the RTTB system – a distributed product development system that supports the separation of design and manufacturing activities.

References

Chen, W., Allen, J.K. and Mistree, F. (1997), "The robust concept exploration method for enhancing concurrent systems design", *Concurrent Engineering: Research and Applications*, Vol. 5 No. 3, pp. 203-17.

Chen, Y. (2001), "Computer-aided design for rapid tooling: methods for mold design and design-for-manufacture", PhD dissertation, Georgia Institute of Technology.

Chen, Y. and Rosen, D.W. (2002a), "A region based method to automated design of multi-piece molds with application to rapid tooling", *ASME Journal of Computing and Information Science in Engineering*, Vol. 2 No. 2, pp. 86-97.

Chen, Y. and Rosen, D.W. (2002b), "A reverse glue approach to automated construction of multi-piece molds", *ASME Journal of Computing and Information Science in Engineering*, (in preparation).

Cho, U., Wood, K.L. and Crawford, R.H. (1999), "Error measures for functional product testing", *ASME Design for Manufacturing Conference*, Paper #DETC99/DFM-8913, 12-16 September, Las Vegas.

Dawson, K. (2001), "The effects of rapid tooling on final product properties", PhD dissertation, Georgia Institute of Technology, Atlanta.

Fernandez, M., Rosen, D.W., Allen, J.K. and Mistree, F. (2002), "Digital interfaces: the key to effective decision-making in distributed collaborative design and manufacture", *ASME Computers and Information in Engineering Conference*, DETC2002/CIE-34466, 29 September-2 October, Montreal.

Fernández, M.G., Seepersad, C.C., Rosen, D.W., Allen, J.K. and Mistree, F. (2001), "Utility-based decision support for selection in engineering design", *ASME Design Automation Conference*, DETC2001/DAC-21106, 9-12 September, Pittsburgh, PA.

Hernandez, G., Allen, J.K. and Mistree, F. (2001), "The compromise decision support problem: modeling the deviation function as in physical programming", *Engineering Optimization*, Vol. 33 No. 4, pp. 445-71.

Lynn-Charney, C.M. and Rosen, D.W. (2000), "Accuracy models and their use in stereolithography process planning", *Rapid Prototyping Journal*, Vol. 6 No. 2, pp. 77-86.

Mistree, F., Hughes, O.F. and Bras, B.A. (1993), "The compromise decision support problem and the adaptive linear programming algorithm", in M.P.K. (Ed.), *Structural Optimization: Status and Promise*, Washington, DC, pp. 247-89.

Myers, R.H. and Montgomery, D.C. (1995), *Response Surface Methodology: Process and Product Optimization using Designed Experiments*, Wiley, New York.

Rosen, D.W. and Gibson, I. (2002), "Decision support and system selection for RP", in Gibson, I. (Ed.), *Book chapter in Software Solutions for RP*, PEP Ltd, London.

Sambu, S.P. (2001), "A design for manufacture method for rapid prototyping and rapid tooling", Masters thesis, Georgia Institute of Technology.

West, A.P., Sambu, S. and Rosen, D.W. (2001), "A process planning method for improving build performance in stereolithography", *Computer-Aided Design*, Vol. 33 No. 1, pp. 65-80.

Xiao, A., Choi, H-J., Kulkarni, R., Allen, J.K., Rosen, D. and Mistree, F. (2001), "A web-based distributed product realization environment", *ASME Computers in Engineering Conference*, DETC2001/CIE-21766, 9-12 September, Pittsburgh, PA.