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RESEARCH ARTICLE

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An application of game theory in distributed collaborative decision making

Abstract In a distributed product realization environment, new paradigms and accompanying software systems are necessary to support the collaborative work of geographically dispersed engineering teams from different disciplines who have different knowledge, experience, tools and resources. To verify the concept of collaboration by separation, we propose a generic information communication medium to enable knowledge representation and exchange between engineering teams, a digital interface. Across digital interfaces, each engineering team maintains its own perspective towards the product realization problem, and each controls a subset of design variables and seeks to maximize its own payoff function subject to individual constraints. Hence, we postulate the use of principles from game theory to model the relationships between engineering teams and facilitate collaborative decision making without causing unnecessary information exchange or iteration across digital interfaces. A product design and manufacturing scenario is introduced to demonstrate the efficacy of using game theory to maintain a clean interface between design and manufacturing teams.

Keywords collaboration, distributed product realization, game theory, digital interface

1 Frame of reference

We believe the appropriate method of implementing collaborative product realization in a distributed environment is to separate the decision-making activities by constructing digital interfaces between the activities. The digital interface must be standard and discipline-independent, and capable of "representing knowledge in computer readable and retrievable format, sharing among collaborative team members, and facilitating design reuse for new concept generation" [1,2]. The notion of a digital interface was initially raised in a National Science Foundation Workshop on Design Methodology for Solid Freeform Fabrication [3] (presently called additive manufacturing, AM). Although originally a digital interface was restricted to a way of transferring only geometric information, we extend the concept to include all types of design knowledge such as design requirements, design rationales and an understanding of system capability and constraints. A digital interface capable of transferring enough information about a product realization activity so that the recipient teams can make decisions without additional information exchange or iteration is called "clean" digital interface [3].

Transferring information between engineering teams is a significant research problem in collaborative product realization. Chao and Wang [4] presented a data exchange framework between different computer aided design (CAD) and computer aided manufacturing (CAM) users, in which AutoCAD files are translated into STEP (Standard for the Exchange of Product Model Data) to enable data sharing. Wu et al. [5] presented cloud-based design and manufacturing as a new paradigm that will "drive digital manufacturing and design innovation". Whitfield et al. [6] presented a Virtual Integration Platform (VIP) for the integration of CAD and computer fluid dynamics models in a distributed environment. Eynard et al. [7] developed Web Computer Supported Cooperative Work (CSCW) for the integration of CAD and finite element analysis (FEA) models. Kleiner et al. [8] presented an extended parametric information model for the integration of computer aided technology (CAx) models, such as FEA and multibody system simulation. Constraints in the design activities are used to represent the parametric relationships between these models and enable knowledge sharing across product development teams. National

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Institute of Standards and Technology developed a standard language, Process Specification Language, to describe multidisciplinary product realization activities from the general perspective [9].

A digital interface is different from product data model or standard, such as STEP, IGES (initial graphical exchange specification), or XML (Extensible Markup Language), which, even though it is capable of providing a complete, unambiguous, and semantically rich definition of the physical and functional characteristics of a product, it fails to capture the design rationale behind the product model. Whitfield et al. [10] pointed out that the implementations of elaborated data representation model such as STEP would be too time-consuming and would significantly increase the complexity of the product realization. The authors suggest developing an abstract data representation that provides an interface for the definition and management of engineering data so that engineers can focus on decision-making problems in product development. Whitfield et al. [11,12] also presented an object-oriented data model within which the abstract data type is a super class above the CAD model, data file, etc. This concept is very similar to the digital interface we presented here. Hoffmann and Joan-Arinyo [13,14] presented the product master model architecture, which is a unified repository containing all the relevant product data that is shared explicitly among the various views, e.g., design and FEA views. Badin et al. [15,16] introduced a knowledge configuration model to manage the knowledge encapsulated and ensure consistency in the product development models. Design Rationale editor (DRed) is a software tool within the Rolls-Royce PLM toolset that allows designers to record design decisions and rationale as the design proceeds [17]. Peng et al. [18] developed a knowledge model that can "combine geometric model, knowledge-based analysis codes and problem-solving strategies and processes". A detailed and thorough review of knowledge representation in product design is presented in Ref. [19], it is noted that completely capturing of design rationales in collaborative product realization activities remains a significant challenge.

In this paper we use the compromise decision support problem (DSP) as a digital interface for design information capturing and sharing. The main purpose of this paper is to present an engineering case to demonstrate the efficacy of using game theoretical principles to keep digital interfaces clean during the product realization process.

1.1 The compromise decision support problem

A compromise DSP is a multi-objective decision model which is a hybrid formulation based on mathematical programming and goal programming. In the compromise DSP, the objective is to satisfy a set of constraints while achieving a set of conflicting goals as well as possible [20–22]. The mathematical formulation of the compromise DSP is given in Fig. 1 [23].

Given

An alternative to be improved

Target value for goals, G_i, $i = 1,2,\ldots,n$

Relative importance of goals, w_i

Find

System variables: $x_j \in X, j = 1,2,\ldots,m$

Deviation variables: d_i^-, d_i^+

Satisfy

Goals: $A_i(X) + d_i^- - d_i^+ = G_i$

Constraints: $g_k(X) \leqslant 0, k = 1,2,\ldots,p$

$d_i^- \cdot d_i^+ = 0, d_i^-, d_i^+ \geqslant 0$

Bounds: $lb_j \leqslant x_j \leqslant ub_j, j = 1,2,\ldots,m$

Minimize

Deviation function:

$$Z = \sum_{i=1}^{n} W_i(d_i^- + d_i^+), \text{ where } \sum_{i=1}^{n} W_i = 1, W_i \geqslant 0$$

Note: Alternative formulations for the deviation function are available

Fig. 1 Mathematical formulation of the compromise DSP [23]

A compromise DSP is capable of representing the design knowledge of an engineering team, as well as the design rationale. A team's decision is represented with a feasible design space, a set of design objectives, and a tradeoff strategy between these design objectives. The design space is located by the bounds of system variables, $[lb_j, ub_j]$, and constraints, g_k. Design objectives and requirements are modeled as design goals, G_i. The deviation variables, d_i^- and d_i^+, specify the difference between the target value for each goal and the actual achievement of that goal (A_i). A team's tradeoff strategy among the goals is determined by the formulation of the deviation function, $Z = \sum_{i=1}^{m} W_i(d_i^- + d_i^+)$. Collaboration between teams is also determined by which team controls which set of design variables, and by which team has higher priority in making decisions. Therefore, the team's capability and constraints, including those within and between activities, can be efficaciously modeled using a compromise DSP. Moreover, once formulated, a compromise DSP can be easily reused by assigning different parameters, mathematical formulations, software tools, etc.

Because of its standard format, a compromise DSP which is used to model the decisions of multidisciplinary teams is also a medium for sharing knowledge among them. A digital interface is a compromise DSP formulated in the most elementary entities, such as mathematical formulations or computer codes, which are easy to understand and implement on a computer. In other words, the abstract data representation proposed in Ref. [10] can be implemented as Fig. 1, while other data types such as CAD files or executable codes are easily embedded or linked to the digital interface. From one perspective, a compromise DSP serves as the interface between an engineering team and the detailed product information and data. From another perspective, it serves as an interface between cooperating teams because their communication is conducted by transferring or sharing a compromise DSP.

1.2 The design and manufacturing interface in the context of AM

In the context of fabricating parts using AM technologies, different information representation formats can be used as digital interfaces between design and manufacturing teams, and the compromise DSPs has proven to be a valuable addition to traditional formats such as STEP, STL (Standard Template Library) and IGES. In a distributed environment, we wish to facilitate the collaboration of design and manufacturing teams by separating their decision-making activities. By “separation”, we mean the responsibility of product development is transferred from design team to the downstream manufacturing teams, while the overall feasibility of the final result is still guaranteed with as little as possible information exchange or iteration. As the manufacturing team is more knowledgeable in product manufacture, it should be able to accomplish design for manufacturing (DfM) more effectively. To eliminate the unnecessary information exchange and iteration, we need to test where along the design timeline we can set the digital interface and separate the design and manufacturing teams. It may be that the design team may only accomplish functional design and preliminary geometric design, while the manufacturing team accomplishes the remaining tasks of product realization, without causing iteration.

Generally, the process of separating design and manufacture involves three steps, as shown in Fig. 2 in which possible activity flows are listed and candidate separation points are located between activities. Engineering teams are then assigned to accomplish these activities and a suitable position for the digital interface is selected. Finally, engineering teams use game theory to makes decisions collaboratively.

A product realization process in the context of AM is shown at top of Fig. 2. At the first step, a manufacturing process and a part material must be selected prior to fabrication. The second step, geometric tailoring, includes any design operations required to ensure manufacturability. Then the part can be manufactured. Three different sequences of activity flows are shown as A, B and C. In some cases, no geometric tailoring may be necessary, as in flow A. For example, when a company orders a prototype from a service bureau, it probably does not change the design to facilitate the AM process. Sometimes however, geometric tailoring is required to ensure that the fabricated

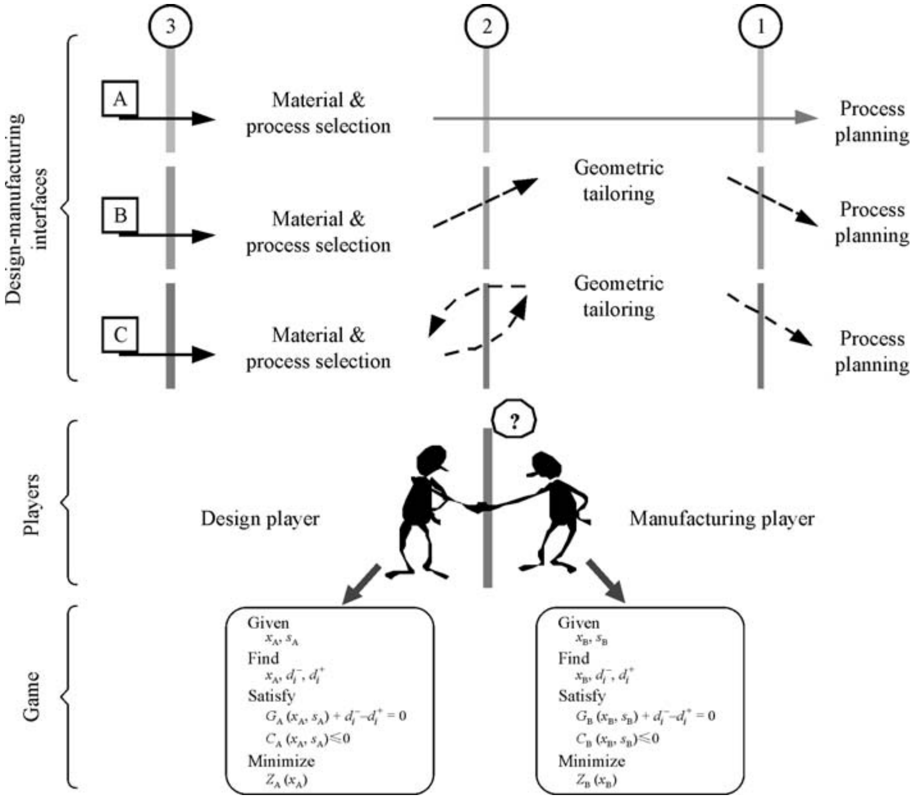


Fig. 2 Design-manufacturing interfaces

(printed) product functions identically to the designed part, flow B. Flow C includes iterations between material and process selection and geometric tailoring. Such iterations are necessary if the selection depends upon the extent of part redesigns to facilitate fabrication. For all possible activity flows, three candidate points indicated by the numbered circles, 1, 2 and 3, are where the design-to-manufacture transfer could occur. Point 1 represents the most secure separation, it is a traditional design and manufacturing scenario, in which a design team accomplishes geometric tailoring and process/material selection. Point 3 represents the most challenging scenario, in which the design team formulates a compromise DSP and sends it to the manufacturing team. The manufacturing team then accomplishes material and process selection, geometric tailoring, and process planning. After deciding the transfer point, as show in the player part of Fig. 2, engineering teams are assigned to these activities, and a compromise DSP is used as a digital interface to separate design and manufacture. Since game theory will be used to solve the compromise DSP, we use the term “player” to represent an engineering team and associated computer-based analysis and synthesis tools. At the bottom of Fig. 2, in the various scenarios proposed, teams solve compromise DSPs and make decisions using game protocols across digital interfaces. In this paper, we only test the second activity flow and the most challenging separation at Point 3.

A digital interface is located at the separation point, where the compromise DSP is transferred (or shared) from the design team to the manufacturing team. If the decisions can be made without additional information exchange or iteration, the digital interface is clean and the product can be developed in a simple and sequential process. However, coupling between teams’ decisions cause iteration. The design team requires input from the manufacturing team, e.g., expected mechanical properties, surface finish, etc., but the manufacturing team cannot supply this information until the final product design has been determined. Therefore, iteration is not due to difficulties with the information representation and communication capability of compromise DSPs, but to couplings in the product realization process.

1.3 The theoretical development of game constructs

There are three possible relationships between two compromise DSPs; they may be solved sequentially, concurrently or as coupled problems. Assume that product realization activities A and B are modeled into compromise DSPs, as shown in Fig. 3, where x_i represents the set of design variables and s_i represents the set of variables that describe the states of the activity, the remaining notation is similar to Fig. 1. Engineering team A and B are assigned to solve the compromise DSPs, respectively.

As shown in Fig. 3, compromise DSPs which are solved concurrently have no common design or state variables. Neither of the teams needs input from the other to make decisions. Hence regardless of the cooperation styles between the team, the same solution is always obtained, in which $\oplus$ represents the combination of the results of two DSPs.

If the design or state variables of one compromise DSP are included in the other, the relationship between these two compromise DSPs is sequential. In Fig. 4, team B uses team A’s design variables and state variables in $\mathrm{DSP_B}$. Hence, team A makes a decision without any input, and this result is essential for team B to make its decision. Regardless their cooperation style, the final solution is always obtained by the downstream team. Moreover, compromise DSPs with concurrent and sequential relationships can be solved without any iteration across the digital interface and the digital interface is always clean.

Coupled compromise DSPs, however, cause iterations across the digital interface, Fig. 5. In this situation, neither compromise DSP can be solved independently because of the shared design variables and state variables, $(x_\mathrm{A}, s_\mathrm{A})$ and $(x_\mathrm{B}, s_\mathrm{B})$. Traditionally, the trial and error method has been used to solve coupled DSPs. Since assumption has to be made to initiate the trial and error process, this traditional

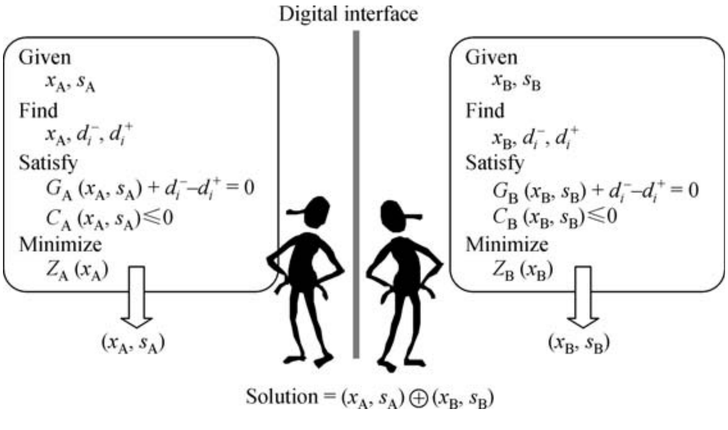


Fig. 3 Solution of concurrent compromise DSPs

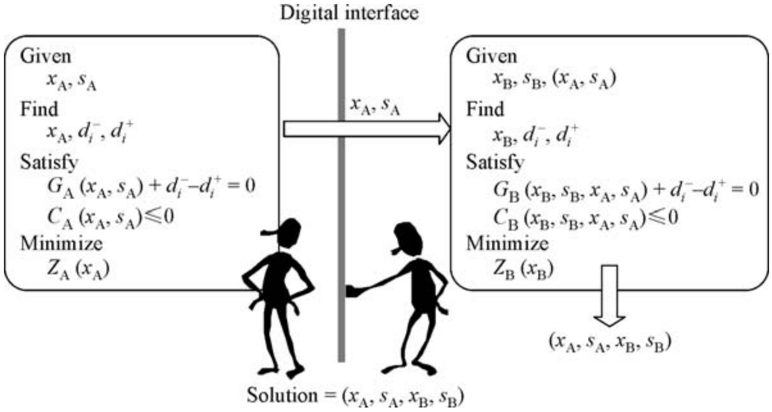


Fig. 4 Solution of sequential compromise DSPs

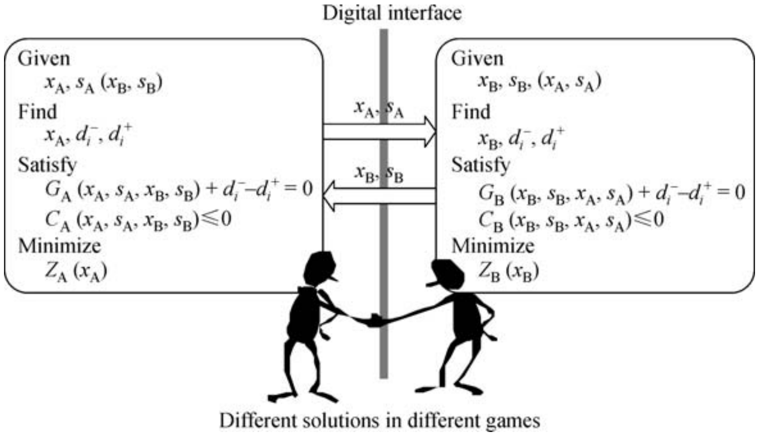


Fig. 5 Game solution of coupled compromise DSPs

approach may not guarantee consensus (convergence) and usually fails to achieve superior results. In this paper, we use game theory to eliminate the iterations between the coupled DSPs, which is capable of facilitates different interaction among multiple engineering teams (or players in game theory terminology): cooperative, noncooperative, and leader/follower relationships. Rao and colleagues [24–27] and Badhrinath and Jagannatha Rao [28] demonstrated cooperative and leader/follower protocols for product realization. Takai [29] presented a game-based model to support the collaboration between teams with diverse background. Xiao et al. [30] presented a multi-objective multidisciplinary design optimization approach based on non-cooperative protocol and gene expression programming. Chen and Li [31] investigated the interaction between product design and manufacturing using all three protocols. Ge and Hu [32] implemented three protocols to support the strategic decision making in a firm's research and development activities. Lewis and Mistree [33,34] presented mathematical constructs for collaborative decision-making using these protocols.

1.3.1 Pareto or cooperative solution

The ideal scenario for collaboration is full cooperation between players in which both players (design and manufacturing) have complete access to the information about each other's decision-making processes, including their compromise DSPs and associated engineering data and tools. The results of a fully cooperative scenario are obtained by combining all players' DSPs, hence all goals, constraints, etc. in design and manufacturing are satisfied in one DSP. Mathematically, this is expressed as

$$\text{minimize} \quad Z = w_A Z_A(x_A) + w_B Z_B(x_B) . \qquad (1)$$

Full cooperation rarely happens in practice because in a distributed environment it is difficult to access all decision-making information of another player. It is also not easy for a player to operate the engineering data and tools associated with players from different disciplines. From the computing perspective, a combined large compromise DSP may contain too many design variables to be solvable. A more practical scenario is one in which a player has only approximate knowledge about the other players' decision-making process, and must predict the other players' decisions based on available information. The available information may be obsolete or inaccurate; therefore, iterations are necessary to reach consensus. Using a Taylor expansion, a player's decision can be predicted based on his/her decision at the last iteration. This mathematics of the game construct is presented in Refs. [33,34]:

$$\begin{cases} s_{\mathrm{A}}^{i}(x) \approx s_{\mathrm{A}}^{i-1} + \nabla s_{\mathrm{A}}(x^{i-1})(x-x^{i-1}) \\ s_{\mathrm{B}}^{i}(x) \approx s_{\mathrm{B}}^{i-1} + \nabla s_{\mathrm{B}}(x^{i-1})(x-x^{i-1}) \end{cases}, \tag{2}$$

in which x^{i-1} and $s_{\mathrm{A}}^{i-1}(x)$ are respectively the values of local design variables and state variables in the previous iteration. The first order derivatives $\nabla s(x)$ are constructed using a Global sensitivity equation approach. Approximate cooperation is also an ideal situation that cannot be expected in practice. Players are inclined to make decisions to maximize their own benefits without considering other players' reactions. A clean digital interface between players becomes impossible because of the iterations; and in a problem with many design variables, an approximate cooperative protocol may not converge.

1.3.2 Nash or noncooperative solution

At the other extreme of collaboration is noncooperation, in which the game players cannot receive additional input beyond the other player's compromise DSPs. Therefore, each player has to make a set of decisions that is rational to it by assuming the other players' reactions, their best reply correspondence (BRC). If there is an overlap between these players' BRCs, the result can be selected from their intersection. A game player constructs a BRC by representing the coupled non-local variables with a set of mathematical formulations of local variables of another player. For instance, in Fig. 5, X_{A} and X_{B} are respectively the design variable sets in players' A and B's compromise DSPs. x_{A} is a subset of X_{A} which must be determined using information from player B's compromise DSP. Then these two player's BRCs are respectively represented as $x_{\mathrm{A}} = f(x_{\mathrm{B}})$ and $x_{\mathrm{B}} = f(x_{\mathrm{A}})$ and the intersection of these BRCs can be found. If a player's BRC cannot be derived mathematically, design of experiment (DOE) techniques and response surface model works well to predict quantitatively a player's reaction to other players' decisions. Using $x_{\mathrm{A}}^{\mathrm{N}}(x_{\mathrm{B}})$ to represent the Nash solution of x_{A}, the mathematics is:

$$\begin{cases} x_{\mathrm{A}}^{\mathrm{N}}(x_{\mathrm{B}}) := \{x_{\mathrm{A}}^{\mathrm{N}} \in X_{\mathrm{A}} : Z_{\mathrm{A}}(x_{\mathrm{A}}^{\mathrm{N}}, x_{\mathrm{B}}) = \min\limits_{x_{\mathrm{A}} \in X_{\mathrm{A}}} Z_{\mathrm{A}}(x_{\mathrm{A}}, x_{\mathrm{B}})\} \\ x_{\mathrm{B}}^{\mathrm{N}}(x_{\mathrm{A}}) := \{x_{\mathrm{B}}^{\mathrm{N}} \in X_{\mathrm{B}} : Z_{\mathrm{B}}(x_{\mathrm{A}}, x_{\mathrm{B}}^{\mathrm{N}}) = \min\limits_{x_{\mathrm{B}} \in X_{\mathrm{B}}} Z_{\mathrm{B}}(x_{\mathrm{A}}, x_{\mathrm{B}})\} \\ (x_{\mathrm{A}}^{\mathrm{N}}, x_{\mathrm{B}}^{\mathrm{N}}) \in x_{\mathrm{A}}^{\mathrm{N}}(x_{\mathrm{B}}) \otimes x_{\mathrm{B}}^{\mathrm{N}}(x_{\mathrm{A}}) \end{cases}. \tag{3}$$

A noncooperative protocol can be implemented across a clean digital interface between players, but the process of searching for intersections can be tedious and difficult. Noncooperative behavior should also be avoided because in product realization, it is beneficial to strive for cooperation.

1.3.3 Stackelberg or leader/follower solution

A leader-follower, or Stackelberg, protocol fits well when one player dominates the decision-making process, or the "influence of a certain domain on another is strongly unidirectional" [33]. When fabricating products with AM technologies, we try to remove the burden of DfM from the design team who can then focus on product design, with the manufacturing team taking as much responsibility as possible. Hence in the game, the manufacturing team must be the leader and the design team the follower. A leader/follower protocol is a special instance of a noncooperative protocol. Assuming player A is the leader, the mathematics is

$$\begin{cases} \text{minimize} \quad Z_{\mathrm{A}}(x_{\mathrm{A}}, x_{\mathrm{B}}) \\ \text{satisfying} \quad x_{\mathrm{B}} \in x_{\mathrm{B}}^{\mathrm{N}}(x_{\mathrm{A}}) \end{cases}. \tag{4}$$

The process of solving a leader/follower game is shown in Fig. 6. In this case, the leader (manufacturing) constructs the follower's (design) BRC.

1) At first, the leader reads in the follower's compromise DSP. Since the follower's decisions do not exceed the design space formed by the bounds of design variables in its compromise DSP, the leader selects a set of points from this space using DOE techniques [35]. In this work, we construct a quadratic model, using full factorial designs with points evenly distributed in the design space (Fig. 6). Hence, 3^n points are selected, where n is the number of variables shared between the coupled DSPs.

2) Second, the leader solves a set of follower's compromise DSPs, and constructs response surface models that represent the coupled design variables and state variables as the functions of the leader's design variables.

3) Third, coupled variables in the leader's compromise DSP are replaced with the follower's BRC. Then the leader solves the compromise DSP without causing additional iteration.

4) Fourth, the follower's compromise DSP is solved based on the leader's decision, which is not shown in Fig. 6.

A leader-follower game protocol facilitates collaborative decision making without iteration, hence clean digital interfaces between game players can be implemented. If the times required to solve design and manufacturing compromise DSPs are respectively t_{d} and t_{m}, and n is the number of shared (coupled) design variables in the manufacturing compromise DSP, it takes approximately $3^n t_{\mathrm{d}} + t_{\mathrm{m}}$ to get results for a full factorial design experiment

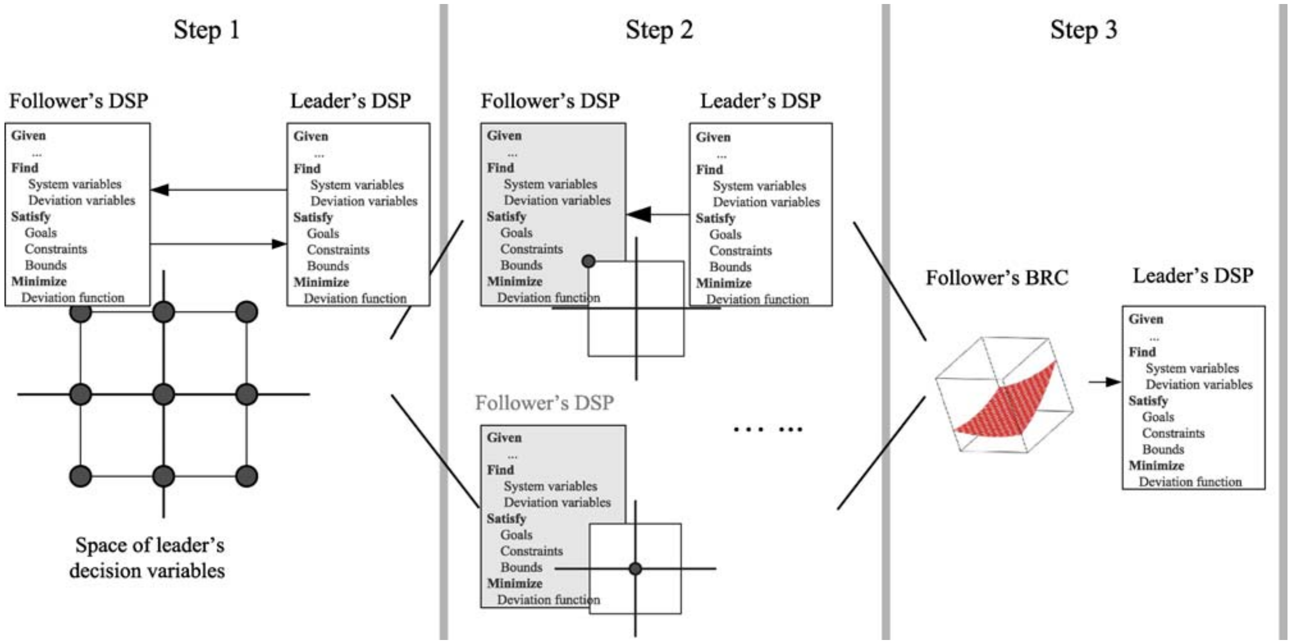


Fig. 6 Solving a leader/follower game

and a quadratic response surface model. Moreover, since manufacturing related decisions are made before the final geometric shape of the product is determined, the leader (manufacturing) in this game has more freedom to explore the design space and therefore can ensure better manufacturability. As the result, a leader/follower game protocol can be used as an effective decision-making approach across a clean digital interface of product design and manufacture.

2 A product realization scenario

In this section, a product realization scenario is presented to clarify the effectiveness of maintaining clean digital interface using various game protocols in distributed collaborative decision making. It needs to be noted that due to the fast development of AM technologies, the equipment and material used in this scenario are no longer the most advanced ones. They are selected simply because the empirical equations that describe the properties of the manufacturing process are readily available in Ref. [36], which can be used to support the decision making across digital interface. Gao et al. [37] presented a thorough review of the recent developments of AM technologies.

A distributed product realization environment is developed based on the activity flow B introduced in Fig. 2. A simple part, the cover plate for a light switch, is developed as shown in Fig. 7. The basic size of the light switch is 80 mm × 120 mm. In order to demonstrate and test the customized product, the customer needs 30 copies within 48 h and the cost must be less than 3000 USD. The light switch will be used in a standard housing and must be disassembled/assembled by hand. The customer wants the printed cover plates to function similar to those mass produced using injection molding and acrylonitrile-butadiene-styrene (ABS).

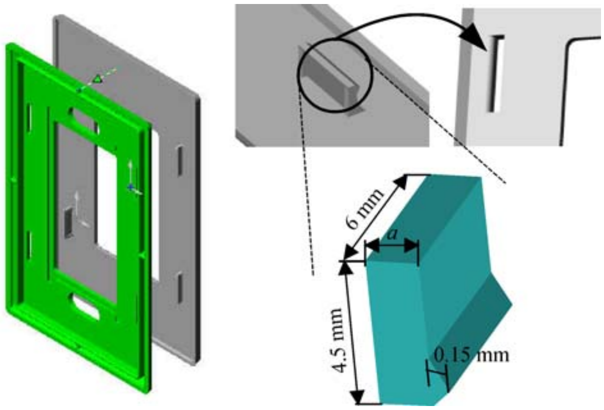


Fig. 7 Light switch cover plate and the snap fit

A design and a manufacturing team are assigned to this task. The product will be developed following activity flow B in Fig. 2, although in this case, geometric tailoring simply involves modifying several geometry dimensions to ensure that the manufactured product function properly. We choose to set the design-manufacturing digital interface at the most challenging point, before material selection and geometric tailoring, Point 3 in Fig. 2. Therefore, the design team will select a material in product design, while the manufacturing team may very likely select a different material to fabricate it. Our objective is to design and fabricate the batch of products without any iteration between design and manufacturing teams.

The product realization process is partitioned into four activities, i.e., product design, material selection, geometric tailoring and process planning. In product design, the design team selects ABS as the material: Good strength, toughness, and electrical resistance, and designs the basic geometric shape of the cover plate. In materials selection, the manufacturing team selects an available resin with properties that are similar to those of ABS, SL-7510, and the machine SLA 3500. In geometric tailoring, the manufacturing team has to modify geometry dimensions to ensure the parts printed using SL-7510 function the same as designed. In process planning, the manufacturing team determines the most suitable fabrication parameters for the SLA 3500. For simplicity, geometric tailoring and material selection activities are combined with process planning in one compromise DSP. It is worth noting that other AM technologies can also be selected, such as fused deposition modeling, but the product realization process remain the same. It follows activity flow B in Fig. 2.

2.1 The design player's compromise DSP

Since the basic dimensions of the cover plate are specified, the design team focuses on the thickness of the cover plate and the snap fit that connects the cover plate to its base. The geometric shape of the snap fit is shown in Fig. 7. In product design, the design variables are a, the thickness of snap fit, and t, the thickness of the cover plate. The customer specifies three goals: (i) The assembly/disassembly force is as close to 2.943 N (0.3 kg-force) as possible, (ii) the deformation of the cover plate during assembly/disassembly is as close to 5 mm as possible, and (iii) the volume of the cover plate should be as small as possible. The target value of volume is the minimal value this goal could achieve given the bounds, 24054 mm^3. Because ABS is the designed material, the design team determines performance target using the properties of ABS. For ABS filled with 10% glass fiber, Young's modulus (E) is 3.5 GPa and its tensile strength (Y) is 59.3 MPa. In this scenario, the final material properties of the printed part are determined by fabrication processes about which the designer has no information. E and Y are coupled state variables within the manufacturing phase. The detailed design compromise DSP is shown in Fig. 8. The equations of deformation properties, D, force, F, and volume, V, are shown in Eqs. (5)–(7). D and F are quadratic response surface models of a FEA model as shown in Fig. 8. V is estimated using the equations in Ref. [36].

$$D(a,t) = 3.77 + 5.39a - 2.81t + 3.04(a-1.5)^2 + 1.22(t-4)^2 - 3.39(t-4)(a-1.5)\,\mathrm{mm}, \quad (5)$$

$$F = 0.741Ea^3, \quad (6)$$

$$V = 9600t + 108a, \quad (7)$$

where F is assembly/disassembly force (Newton), and E is Young's modulus (GPa).

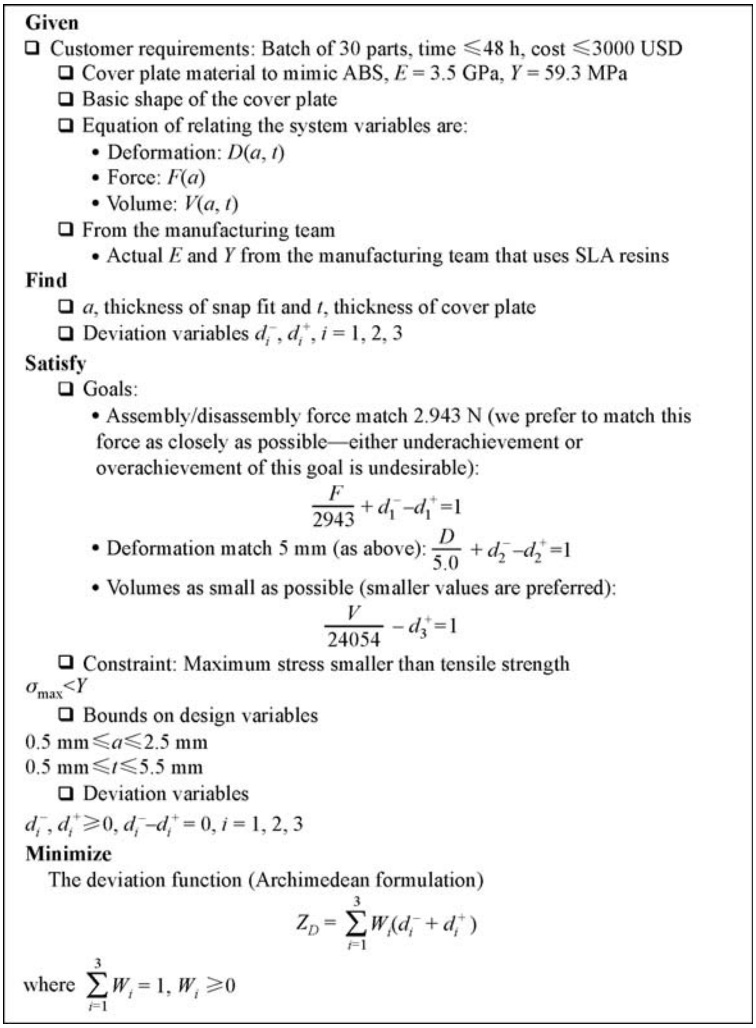
The design compromise DSP is formulated with detailed mathematical functions. The computer implementation of this compromise DSP forms the design team's digital interface which is then sent to the manufacturing team. From this interface the manufacturing team learns the necessary information about the product design. The design team can either transfer the compromise DSP as a text file or as a piece of code which accepts input E and Y and generates output a and t. The manufacturing team does not need to know the detailed software operation and data processing in the design activity, while still be able to make correct design decisions by doing the calculation or running the code.

2.2 The manufacturing player's compromise DSP

The manufacturing compromise DSP is shown in Fig. 10. There are three system variables to be determined: Layer thickness, LT; hatch overcure, HOC; and fill overcure, FOC. The five goals are: (i) The least possible time, (ii) least cost, (iii) surface finish as smooth as possible (this is measured by the largest roughness on the part where support structure is generated), (iv) the final Young's modulus as close to 3.5 GPa as possible, and (v) tensile strength as large as possible. Clearly, some targets for these goals are obtained from the design compromise DSP, such as Young's modulus and tensile strength. The manufacturing team assigns the other three target values based on its experience. For instance, the target value for time is set as 20 h, which the manufacturing team thinks is difficult to achieve and can serve as a target. A corresponding constraint, $PT \leqslant 48$ h, is added to ensure the customer requirements are meet. In addition, the layer thickness is a discrete variable with only three possible values: 2, 4 and 8 mil (1 mil = 0.0254 mm). The bounds of HOC and FOC differ with the value of LT. Detailed derivations of Eqs. (8) to (12) are presented in Ref. [36]. English units mil and μin (1 μin = 25.4×10^{-6} mm) are used here because these are the only units for the setting of the machine. Obviously, the manufacturing team cannot determine these variables without knowing the final geometric information about the cover plate, including t and a.

$$\mathrm{cost} = \mathrm{BS} \times (65\mathrm{BT} + 30), \quad (8)$$

where BT is the single product build time (unit: h), BS is batch size, and the unit of the cost is USD. BT = Part build time + Support build time. Surface finish is described using roughness, y, of the surface. It is estimated using a set of experimental equations.



Given

- ☐ Customer requirements: Batch of 30 parts, time $\leqslant$48 h, cost $\leqslant$3000 USD
  - ☐ Cover plate material to mimic ABS, $E = 3.5$ GPa, $Y = 59.3$ MPa
  - ☐ Basic shape of the cover plate
  - ☐ Equation of relating the system variables are:
    - Deformation: $D(a, t)$
    - Force: $F(a)$
    - Volume: $V(a, t)$
  - ☐ From the manufacturing team
    - Actual E and Y from the manufacturing team that uses SLA resins

Find

- ☐ a, thickness of snap fit and t, thickness of cover plate
- ☐ Deviation variables $d_i^-, d_i^+, i = 1, 2, 3$

Satisfy

- ☐ Goals:
  - Assembly/disassembly force match 2.943 N (we prefer to match this force as closely as possible—either underachievement or overachievement of this goal is undesirable):

$$\frac{F}{2943} + d_1^- - d_1^+ = 1$$

  - Deformation match 5 mm (as above): $\frac{D}{5.0} + d_2^- - d_2^+ = 1$
  - Volumes as small as possible (smaller values are preferred):

$$\frac{V}{24054} - d_3^+ = 1$$

- ☐ Constraint: Maximum stress smaller than tensile strength

$\sigma_{\max} < Y$

- ☐ Bounds on design variables

$0.5 \text{ mm} \leqslant a \leqslant 2.5 \text{ mm}$

$0.5 \text{ mm} \leqslant t \leqslant 5.5 \text{ mm}$

- ☐ Deviation variables

$d_i^-, d_i^+ \geqslant 0, d_i^- - d_i^+ = 0, i = 1, 2, 3$

Minimize

The deviation function (Archimedean formulation)

$$Z_D = \sum_{i=1}^{3} W_i(d_i^- + d_i^+)$$

where $\sum_{i=1}^{3} W_i = 1, W_i \geqslant 0$

Fig. 8 The design player's compromise DSP

Up facing surface models:

$$\begin{cases} LT = 2 \text{ mil, build orientation between } (0°,90°),\ y = 58729979x^2 + 16441x + 64 \\ LT = 4 \text{ mil, build orientation between } (0°,15°),\ y = -46917308831x^2 + 365676540x - 711625 \\ LT = 4 \text{ mil, build orientation between } (15°,90°),\ y = 43263055x^2 + 16028x + 131 \\ LT = 8 \text{ mil, build orientation between } (0°,30°),\ y = -1919977114x^2 + 27802608x - 98799 \\ LT = 8 \text{ mil, build orientation between } (30°,90°),\ y = -23917363x^2 + 349649x + 406 \\ \text{Any layer thickness, build orientation is } 0°,\ y = 6 \end{cases} . \qquad (9)$$

Down facing surfaces:

$$\begin{cases} LT = 2 \text{ mil, build orientation between } (90°,150°),\ y = 150441348x^2 - 146261x + 76 \\ LT = 2 \text{ mil, build orientation between } (150°,180°),\ y = 9778267616x^2 - 35966307x + 33258 \\ LT = 4 \text{ mil, any build orientation, } y = 609302230x^2 - 177900x + 164 \\ LT = 8 \text{ mil, any build orientation, } y = 27102824x^2 - 198948x + 429 \\ \text{Any layer thickness, build orientation is } 180°,\ y = 243 \end{cases} , \qquad (10)$$

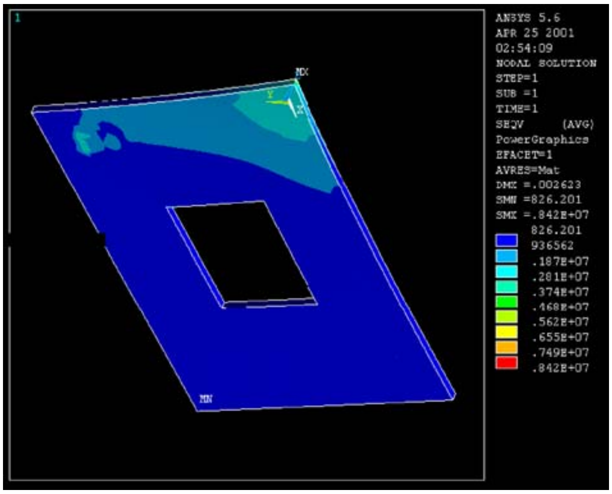


Fig. 9 Finite element analysis of cover plate

where x is cusp height (unit: in, 1 in = 25.4 mm), and y is roughness (unit: μin).

$$\begin{aligned}&\text{Young's modulus}\\&=903.42+121LT+498HOC+0.15LT^2\\&\quad-25.75HOC^2-33.25LT\cdot HOC,\end{aligned}\tag{11}$$

$$\begin{aligned}&\text{Tensile strength}\\&=24.6948+6.1168LT+4.5286HOC-0.4844LT^2\\&\quad-0.1706HOC^2-0.3326LT\cdot HOC,\end{aligned}\tag{12}$$

where LT is the layer thickness (unit: mil, 1 mil = 0.0254 mm), HOC is the hatch overcure (unit: mil), FOC is fill overcure (unit: mil), and the unit of Young's modulus and tensile strength is MPa.

These compromise DSPs pack design requirements and knowledge about the design space and the capability and constraints of product design and manufacturing into integrated decision models. The part's CAD model cannot be explicitly represented in the compromise DSP hence is linked as a data file. The teams can exchange their information using compromise DSPs as digital interfaces. Since neither of these compromise DSPs can be solved independently because they are coupled by the geometric information a and t and the knowledge of the manufacturing result Y and E, the principles of game theory are used to solve them. Depending upon the cooperation between design and manufacturing game players, three different games are formulated. In the cooperative game, all eight goals in both compromise DSPs are satisfied together.

$$\min\ Z_{\text{game}}=w_{\text{D}}Z_{\text{D}}+w_{\text{M}}Z_{\text{M}}.\tag{13}$$

Sometimes, players cannot communicate because of barriers to information exchange in the distributed environment, so a noncooperative game is formulated. The mathematical formulation of a noncooperative game is

$$\min\ Z_{\text{M}}(\text{BRC}_{\text{D}})\otimes\min\ Z_{\text{D}}(\text{BRC}_{\text{M}}).\tag{14}$$

If a design compromise DSP can be successfully transferred to the manufacturing player, a leader/follower game is formulated. When the manufacturing team is leader,

$$\min\ Z_{\text{M}}(\text{BRC}_{\text{D}}).\tag{15}$$

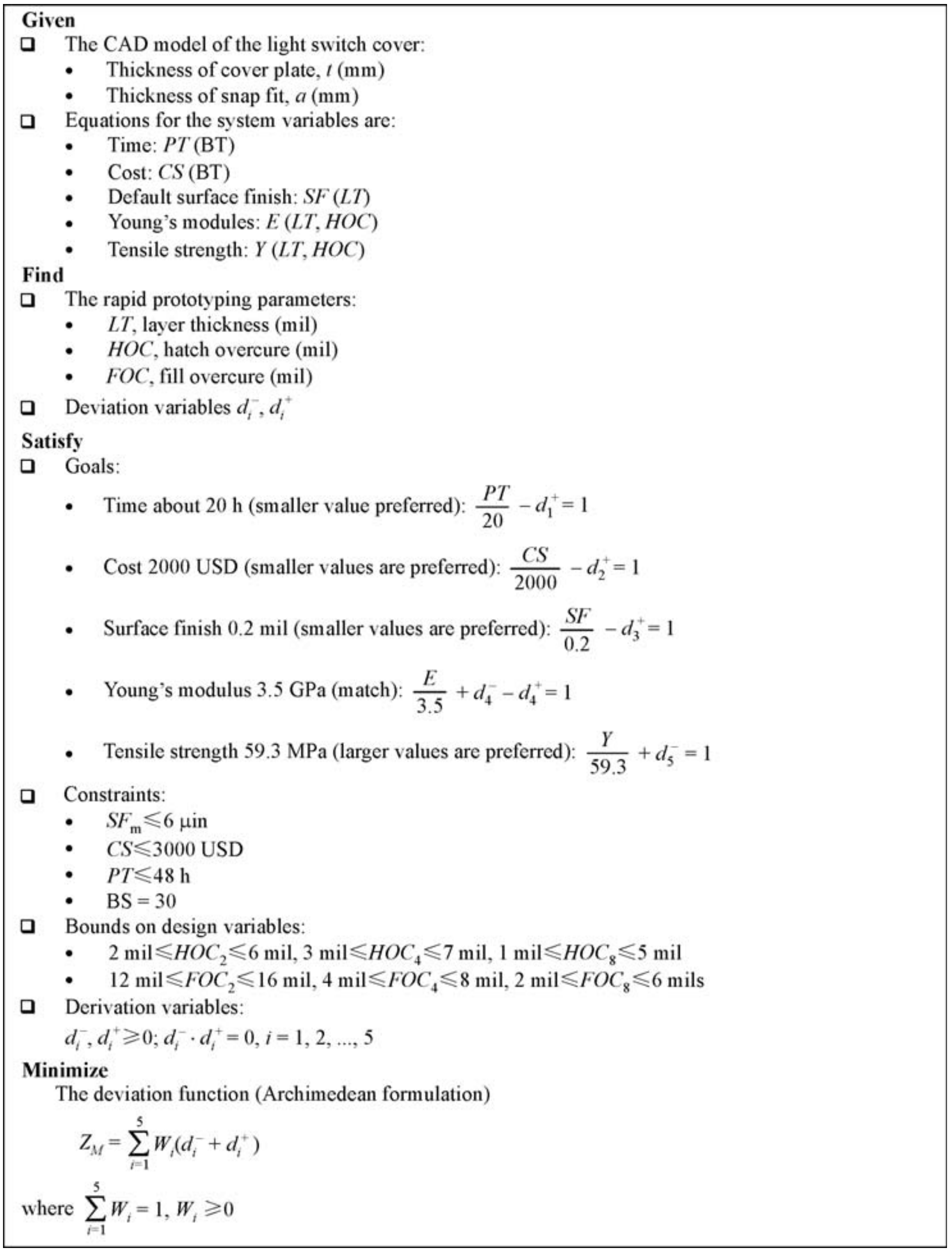
3 Results from game protocols

In this section, the coupled design and manufacturing problem is solved using the three protocols, and the effects of the choice of game protocols on the results are discussed. For the purpose of comparison, the results obtained using traditional trial and error methods is also presented. To ensure that the results are comparable, in each case all goals are assigned equal weights. Generally, the smaller the deviation value, the better the results. A simple flow chart of the solution process of games on a computer is presented in Fig. 11.

The solution process basically follows the mathematical formulation presented in Section 2.3. First, the compromise DSPs for design and manufacturing are formulated and the appropriate game constructs are identified. There are two steps to solving cooperative games, combining and then solving the compromise DSPs. Solving noncooperative games is a concurrent process, in which both players design experiments, solve a set of compromise DSPs, construct mathematical functions of players' BRCs and search for the intersection. In a leader/follower game only the design player (follower) goes through the process of constructing a BRC.

3.1 Results of trial and error approach

Solving a coupled design and manufacturing problem using the trial and error approach is a simulation of the traditional decision-making process in product realization. In this case, the design player starts with the material properties of ABS which are E = 3.5 GPa and Y = 59.3 MPa. Then the design compromise DSP is solved resulting in a = 1.0 mm and t = 3.1 mm. The manufacturing player makes decisions using the actual material properties of SL7510 resin and obtains the values of E = 2.3 GPa, and Y = 46.3 MPa. The part is then redesigned in the geometric tailoring stage. After several iterations, the final results of the design and manufacturing compromise DSPs converge are listed in Table 1.



Given

☐ The CAD model of the light switch cover:
  - Thickness of cover plate, t (mm)
  - Thickness of snap fit, a (mm)

☐ Equations for the system variables are:
  - Time: PT (BT)
  - Cost: CS (BT)
  - Default surface finish: SF (LT)
  - Young's modules: E (LT, HOC)
  - Tensile strength: Y (LT, HOC)

Find

☐ The rapid prototyping parameters:
  - LT, layer thickness (mil)
  - HOC, hatch overcure (mil)
  - FOC, fill overcure (mil)

☐ Deviation variables d_i^-, d_i^+

Satisfy

☐ Goals:
  - Time about 20 h (smaller value preferred): $\frac{PT}{20} - d_1^+ = 1$
  - Cost 2000 USD (smaller values are preferred): $\frac{CS}{2000} - d_2^+ = 1$
  - Surface finish 0.2 mil (smaller values are preferred): $\frac{SF}{0.2} - d_3^+ = 1$
  - Young's modulus 3.5 GPa (match): $\frac{E}{3.5} + d_4^- - d_4^+ = 1$
  - Tensile strength 59.3 MPa (larger values are preferred): $\frac{Y}{59.3} + d_5^- = 1$

☐ Constraints:
  - $SF_{\mathrm{m}} \leqslant 6\ \mu\mathrm{in}$
  - $CS \leqslant 3000$ USD
  - $PT \leqslant 48$ h
  - BS = 30

☐ Bounds on design variables:
  - 2 mil$\leqslant HOC_2 \leqslant$6 mil, 3 mil$\leqslant HOC_4 \leqslant$7 mil, 1 mil$\leqslant HOC_8 \leqslant$5 mil
  - 12 mil$\leqslant FOC_2 \leqslant$16 mil, 4 mil$\leqslant FOC_4 \leqslant$8 mil, 2 mil$\leqslant FOC_8 \leqslant$6 mils

☐ Derivation variables:

$d_i^-, d_i^+ \geqslant 0;\ d_i^- \cdot d_i^+ = 0,\ i = 1, 2, \ldots, 5$

Minimize

The deviation function (Archimedean formulation)

$$Z_M = \sum_{i=1}^{5} W_i(d_i^- + d_i^+)$$

where $\sum_{i=1}^{5} W_i = 1,\ W_i \geqslant 0$

Fig. 10 The manufacturing player's Compromise DSP

Given a good starting point, results converge within 3–4 iterations. Most of the goals come very close to their target values. The overall deviation is calculated with equal weights. Because this procedure requires several iterations, the digital interface between design and manufacture is not clean. The design burden is also heavy because geometric tailoring has to be accomplished by the design team.

3.2 Fully cooperative protocol

The fully cooperative protocol is implemented by combining two compromise DSPs as Eq. (1), and an approximate cooperative protocol is implemented using the first order Taylor expansion (Eq. (2)). In this problem, results from the fully and approximate cooperative protocols are identical as shown in Table 2. We use an exhaustive search method to solve the combined compromise DSPs. For complex problems, a combined DSP may be unsolvable because it may be nonlinear or may include multiple discrete and continuous variables.

The ideal situation has a slightly smaller overall deviation than that of the traditional trial and error approach; thus, there is better overall goal achievement. But the results from the fully cooperative protocol are not necessarily optimal. Different players have different goals

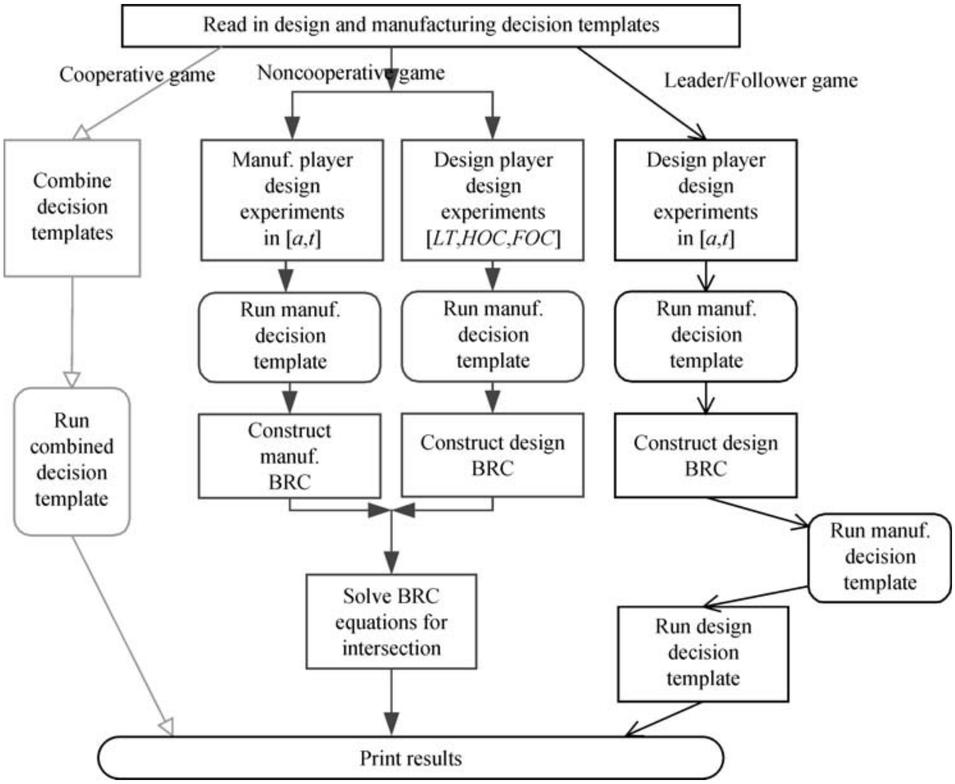


Fig. 11 Solution process for games (manuf.: Manufacturing)

Table 1 Results from the traditional trial-and-error approach

Variable	Value	Deviation
System variable		
a/mm	1.197	**0.165136**
t/mm	2.500	
LT/mil	8.000	
HOC/mil	2.649	
FOC/mil	2.000	
State variable		
Force/N	2.946	$d^+ = 0.000539$, $d^- = 0$
Deformation/mm	4.680	$d^+ = 0$, $d^- = 0.063965$
Volume/mm^3	24129.280	$d^+ = 0.003129$, $d^- = 0$
Time/h	24.630	$d^+ = 0.231500$, $d^- = 0$
Cost/USD	2500.900	$d^+ = 0.250449$, $d^- = 0$
Finish/mil	0.243	$d^+ = 0.215000$, $d^- = 0$
E/GPa	2.350	$d^+ = 0$, $d^- = 0.338601$
Y/MPa	46.380	$d^+ = 0$, $d^- = 0.217904$

Table 2 Results from fully cooperative protocol

Variable	Value	Deviation
System variable		
a/mm	1.220	**0.160609**
t/mm	2.500	
LT/mil	8.000	
HOC/mil	1.600	
FOC/mil	2.000	
State variable		
Force/N	2.943	$d^+ = 0$, $d^- = 0$
Deformation/mm	4.880	$d^+ = 0$, $d^- = 0.023933$
Volume/mm^3	24131.760	$d^+ = 0.003233$, $d^- = 0$
Time/h	23.990	$d^+ = 0.199500$, $d^- = 0$
Cost/USD	2459.480	$d^+ = 0.229739$, $d^- = 0$
Finish/mil	0.243	$d^+ = 0.215000$, $d^- = 0$
E/GPa	2.186	$d^+ = 0$, $d^- = 0.375343$
Y/MPa	45.180	$d^+ = 0$, $d^- = 0.238122$

and thus they may use different weights for the goals, which would result in different values of the overall deviation. Hence a superior result in an ideal situation does not necessarily guarantee a superior result from the perspective of a certain player, who is only concerned about that player's individual goals.

3.3 Noncooperative protocol

The noncooperative game of this case is presented as Eq. (13). The manufacturing player's BRC consists of quadratic response surface models of *LT*, *HOC*, and *FOC*. The experiment points and corresponding results are shown in Table 3.

The design player solves a set of manufacturing compromise DSPs with changing values of *a* and *t*. In this case, *LT* and *FOC* are always 8 and 2 mil; therefore, only the *HOC* values are shown in the table. If $t = 5.5$ mm, the manufacturing player fails to make decisions because the time and cost constraints are violated and the value of $HOC = 0$ mil is assigned here. Since $HOC \in [1,5]$ mils, the response model of *HOC* can still satisfy the accuracy requirements. Concurrently the manufacturing player constructs the BRC of the design team by representing *a* and *t* in the form of *f*(*LT*, *HOC*, *FOC*). Since *HOC* has different bounds at each *LT* value, we select the largest bounds in the experiments which may cause some errors. One method of handling this problem is to construct different response surface models at different *HOC* bounds, and use the average value to solve the design compromise DSP. Using MiniTab®, both players' BRCs are constructed.

$\mathrm{BRC}_{\mathrm{Design}}$:

$$\begin{cases} a(LT,HOC) = 1.50 - 0.0296LT - 0.103HOC \\ +0.00632LT\cdot HOC + 0.000333LT^2 + 0.00591HOC^2 \\ t(LT,HOC) = 2.85 - 0.0376LT - 0.0996HOC \\ +0.00567LT\cdot HOC + 0.00035LT^2 + 0.00665HOC^2 \end{cases}, \tag{16}$$

$\mathrm{BRC}_{\mathrm{Manufacture}}$:

$$\begin{cases} HOC(a,t) = 1.37 - 0.00333a + 1.15t \\ -0.000167a^2 - 0.254t^2 + 0.000667at \\ FOC = 2.0 \text{ mil}, \ LT = 8 \text{ mil} \end{cases}. \tag{17}$$

The results of a noncooperative game, shown in Eq. (14), are obtained by combining and solving the above equations, Table 4. The overall deviation is obviously larger than that of the fully cooperative protocol, which adds weight to the view that usually players cannot make superior decisions when there is lack of cooperation. Each player considers only the local benefit when making isolated decisions, which can impair the overall objective of the product realization process. The large deviation value could also be due to errors introduced during construction of the response surface models.

3.4 Leader/Follower protocol

The leader/follower protocol is a special case of the noncooperative protocol, but the decision-making principles are different. In a noncooperative protocol, players make decisions concurrently, and a final solution is derived from the intersection of players' BRCs. The leader/follower protocol is a more practical simulation of a product realization process in which other players make decisions considering the dominant player's decision. The results of the leader/follower game, Eq. (15), are the same as those obtained by using a trial and error approach, as shown in Table 1. These results are superior to those from the noncooperative protocol. Therefore, cooperation, in any form, can improve engineers' decisions from the overall perspective. Although the manufacturing player makes a decision by assuming the design player's reaction, and errors are introduced when constructing the follower's BRC, superior decisions can still be made using the leader/follower protocol. Note that a solution which is as "good" as that obtained using the traditional trial and error approach is believed to be superior, or good enough.

Some interesting observations can be made by analyzing the various solutions. First, the cover plate thickness, *t*, layer thickness, *LT*, and fill overcure, *FOC*, remain unchanged in all three protocols. This is because the cover plate has a large flat surface and is fabricated with snap fits facing down. Because the build time of the selected AM machine is mostly decided by the part's projection area on the platform and the part height after orientation, *t* dominants the building time. In this case, the constraint, $PT \leqslant 48$ h, forces the lower bound of $t = 2.5$ mm

Table 3 Experimental results of noncooperative games

Experiment	Design player				Manufacturing player		
	LT	*a*	*t*	*HOC*	*a*	*t*	*HOC*
1	2	1.367	2.714	1	0.5	2.5	2.651
2	2	1.173	2.500	4	0.5	4.0	1.897
3	2	1.110	2.500	7	0.5	5.5	0.000
4	4	1.319	2.637	1	1.5	2.5	2.649
5	4	1.177	2.500	4	1.5	4.0	1.896
6	4	1.140	2.500	7	1.5	5.5	0.000
7	8	1.239	2.508	1	2.5	2.5	2.647
8	8	1.183	2.500	4	2.5	4.0	1.894
9	8	1.210	2.500	7	2.5	5.5	0.000

Table 4 Results from a noncooperative protocol

Variable	Value	Deviation
System variable		
a/mm	1.320	**0.200169**
t/mm	2.640	
LT/mil	8.000	
HOC/mil	1.900	
FOC/mil	2.000	
State variable		
Force/N	3.798	$d^+ = 0.291831$, $d^- = 0$
Deformation/mm	4.990	$d^+ = 0$, $d^- = 0.001693$
Volume/mm^3	24486.560	$d^+ = 0.059556$, $d^- = 0$
Time/h	24.100	$d^+ = 0.205000$, $d^- = 0$
Cost/USD	2466.790	$d^+ = 0.233394$, $d^- = 0$
Finish/mil	0.243	$d^+ = 0.215000$, $d^- = 0$
E/GPa	2.230	$d^+ = 0$, $d^- = 0.363182$
Y/MPa	45.560	$d^+ = 0$, $d^- = 0.231694$

and upper bound of $LT = 8$ mil be selected. *FOC* is driven to the lower bound, $FOC = 2$ mil, because of the Young's modulus and tensile strength targets. That is, since the product must satisfy the deformation and disassembly/assembly force requirements, the minimal *FOC* within the range $2\ \text{mil} \leqslant FOC_8 \leqslant 6$ mil is chosen so that a more solid product can be built. This is reasonable from the engineering perspective, hence demonstrates the validity of the decision-making approach.

Response surface methodology and DOE techniques provide the game player tools for predicting players' behaviors, as shown in Fig. 12. In process planning, since *LT* and *FOC* are mostly controlled by the time constraints, only *HOC* is directly affected by the product design. In the *HOC* response surface, it is clear that *t* has an important influence on *HOC*, and *a* does not. *a* is the thickness of snap fits which have a small projection area, and hence *a* does not dominate the process planning parameters. As shown in the left graph in Fig. 12, when *t* changes from its lower to its upper bounds, *HOC* reduces rapidly in order to build the prototypes in shorter time. When *t* reaches 4.5–5.5 mm, the manufacturing player can no longer accomplish its task.

Response surface models of *a* and *t* in Fig. 12 also explain the effects of a manufacturing team's decisions on product design. When building the product using AM technologies, low *LT* and *HOC* values result into long times, but high product quality, such as good surface finish, high strength. If the manufacturing player selects lower values for *LT* and *HOC*, it means the manufacturing player has the capability of handling this task. Then design player enjoys more freedom to change the design to meet other customer requirements. However, in this scenario, *LT* is at its upper bound, which restrains the scope of *a* and *t* that the designer can explore without sacrificing product quality. This also demonstrates that the DfM process depends greatly on product manufacturability and the capability of the manufacturing team.

The deviation values are represented in Fig. 13 in which the deviations from the goals for each protocol are compared. Clearly, the general design goals are satisfied well except the force goal from the noncooperative protocol. Relatively, the manufacturing goals are more difficult to achieve, as shown by larger deviation values. As the cover plate is oriented with snap fits facing down, the largest roughness happens at the large flat surface on which the support structure is generated. From Eq. (9), the roughness for this orientation maintains a consistent value, 0.243 mil, shown as the same deviation values of the surface finish goal in all the games. It is also shown that in this case, different protocols do not greatly differentiate between the product design and manufacturing results.

In Fig. 14, the overall deviation of this problem and the deviation of design and manufacturing from different protocols are shown. The fact that noncooperative protocols show the worst overall deviation and the fully cooperative protocol achieves the best result is not unexpected. Also, the very similar manufacturing deviations in all protocols reveal that different product design

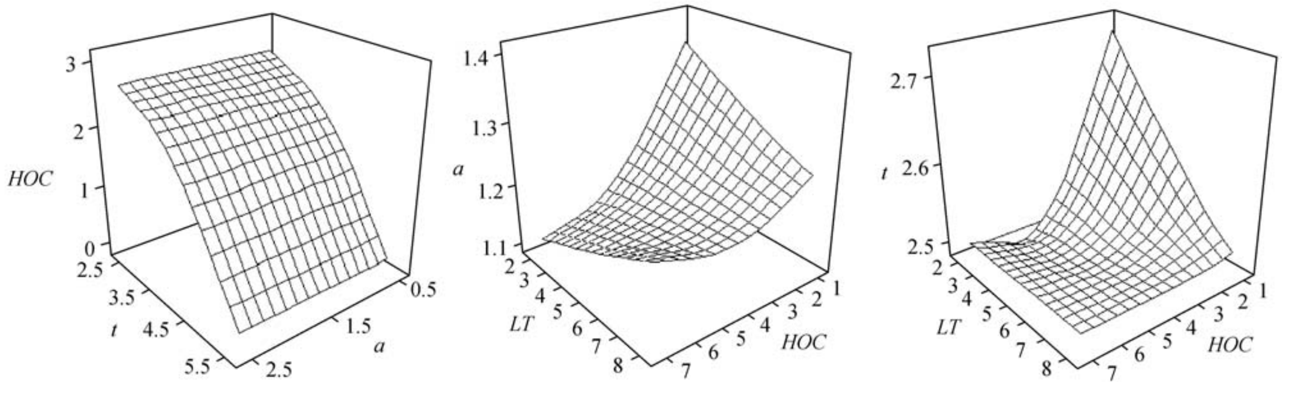


Fig. 12 Response surface model of *HOC*, *a* and *t*

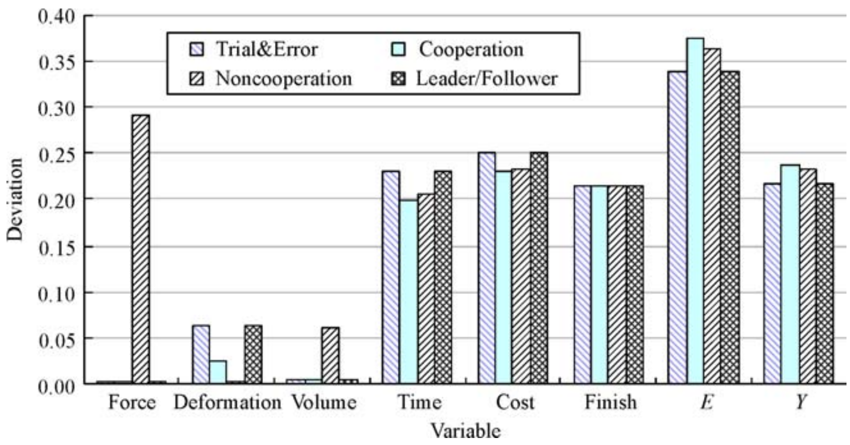


Fig. 13 Deviation values of goals

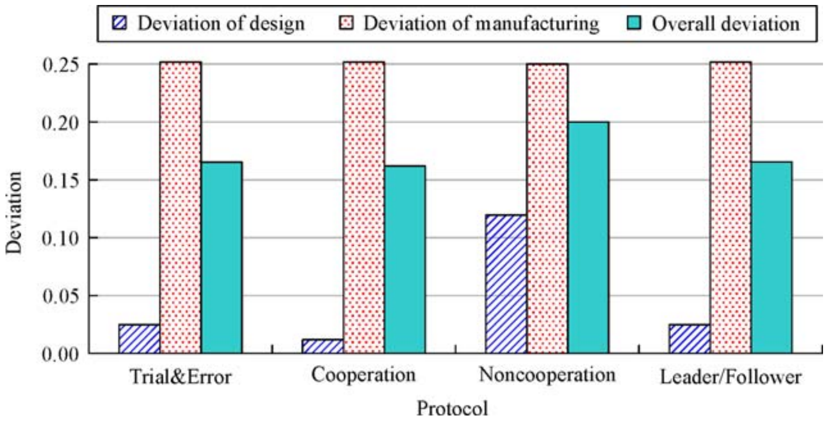


Fig. 14 Deviation values of design and manufacturing

and collaboration protocols do not significantly influence the manufacturing process. This strengthens the statement that AM technologies are flexible enough to fabricate a product without being greatly constrained by its design. As far as the deviation from the design goals, the cooperative protocol yields a superior design. The significantly inferior design resulting from the noncooperative protocol explains that without cooperation with a manufacturing team, a design team cannot design a superior product even when powerful manufacturing capability is available.

Also, in Fig. 14, in the leader/follower protocol, the manufacturing deviation is slightly better than in a fully cooperative protocol. The reason for this is that the manufacturing player makes decisions before the design player does and the manufacturing player enjoys a larger design space and more freedom to select superior fabrication parameters. In the fully cooperative protocol, although the manufacturing player can also explore the entire design space, he/she cannot dominate the process because all goals should be satisfied at the same time. In the traditional trial and error protocol, because the design player decides the exact product shape, the manufacturing player can only search within a smaller design space and cannot find a superior result from the overall perspective. Since our research objective is to give manufacturing team more responsibility, a leader/follower protocol is shown to be effective. Again, although the leader/follower protocol and trial and error approach deliver the same solution, decisions in the leader/follower game are made without causing iteration across the digital interface, hence it keeps the interface clean.

4 Closure

In this paper, an engineering example is presented to verify the idea of collaboration by separation. In the context of fabricating parts using AM technologies, we facilitate collaborative product realization by constructing clean digital interfaces between engineering teams. Clean digital interfaces separate the activities of engineering teams and organize the product realization process into a simple and sequential architecture. In the cases presented in Section 2, activity flow B and separation Point 3, noncooperative and leader/follower protocols facilitate collaborative decision making without causing iteration (Tables 1 and 4). Therefore, the digital interface between design and manufacturing teams is clean. The clean digital interface is proven to be effective in a distributed environment in which information transfer is difficult and some information may not be available. There are some interesting points obtained from our research:

1) A distributed environment may impair cooperation between engineering teams, but collaboration can still be implemented by constructing clean digital interfaces between these teams and making decisions using game theoretical principles;

2) A compromise DSP is capable of representing an engineering team's knowledge and rationales; this formulation can be shared with and understood by other teams;

3) In the context of fabricating product using AM technologies, at least for simple parts, design can be successfully separated from manufacturing immediately following geometric shape design. The manufacturing team is capable of accomplishing material and process selection, DfM or geometric tailoring, and process planning. In this case, the most ambitious design to manufacturing transfer point, Point 3 of activity flow B, Fig. 2 is demonstrated.

4) When solving coupled design and manufacturing problems, the traditional trial and error approach causes iterations, which should be avoided. Fully cooperation requires engineering teams be able to access all information and solve a compromise DSP comprising all the design variables; this usually cannot be achieved. Noncooperation cannot guarantee superior decisions and should be avoid also. The leader/follower approach is an effective game protocol that can help engineering teams make superior decisions.

5) In practice, we do not have to solve all three games for one problem. The choice of game protocols is determined by considering customer requirements and specific situations and the anticipated availability of information at different stages in the product realization process. A noncooperative game, in this case, is solved when information exchange between engineering teams is difficult. A leader/follower game should be solved when one game player dominates the decision-making process. A cooperative game is solved when players are familiar with each other's activities or when players want to explore the most preferable scenario. Generally, cooperation should be encouraged, and noncooperation should be avoided whenever it is possible.

Although we have made progress we also recognize that but a single example has been presented here and the successful separation of design and manufacturing activities relies greatly on the flexible AM technology. However, we believe that the separation of engineering teams using a clean digital interface is useful for implementing collaborative product realization in a distributed environment.

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References

1. Li W D, Lu W F, Fuh J Y H, et al. Collaborative computer-aided design—Research and development status. Computer Aided Design, 2005, 37(9): 931–940
2. Wang L, Shen W, Xie H, et al. Collaborative conceptual design—State of the art and future trends. Computer Aided Design, 2002, 34(13): 981–996
3. Rosen D, Chen Y, Gerhard J, et al. Design decision templates and their implementation for distributed design and solid freeform fabrication. In: Proceedings of ASME Computers and Information in Engineering Conference. Baltimore: ASME, 2000
4. Chao P, Wang Y. A data exchange framework for networked CAD/CAM. Computers in Industry, 2001, 44(2): 131–140
5. Wu D, Rosen D W, Wang L, et al. Cloud-based design and manufacturing: A new paradigm in digital manufacturing and design innovation. Computer Aided Design, 2015, 59: 1–14
6. Whitfield R I, Duffy A H B, Gatchell S, et al. A collaborative platform for integrating and optimizing computational fluid dynamics analysis requests. Computer Aided Design, 2012, 44(3): 224–240
7. Eynard B, Liénard S, Charles S, et al. Web-based collaborative engineering support system: Applications in mechanical design and structural analysis. Concurrent Engineering, Research and Applications, 2005, 13(2): 145–153
8. Kleiner S, Anderl R, Gräb R. A collaborative design system for product data integration. Journal of Engineering Design, 2003, 14(4): 421–428
9. Schlenoff C, Gruninger M, Creek T, et al. The essence of the process specification language. Transactions of the Society for Computer Simulation, 1999, 16(4): 204–216
10. Whitfield R, Duffy A H, Coates G, et al. Distributed design coordination. Research in Engineering Design, 2002, 13(4): 243–252
11. Whitfield R I, Duffy A H B, Boyle I, et al. An integrated environment for organisational decision support. Computers in Industry, 2011, 62(8–9): 842–853
12. Whitfield R I, Duffy A H B, York P, et al. Managing the exchange of engineering product data to support through life ship design. Computer Aided Design, 2011, 43(5): 516–532
13. Hoffmann C M, Joan-Arinyo R. Distributed maintenance of multiple product views. Computer Aided Design, 2000, 32(7): 421–431
14. Hoffman C M, Joan-Arinyo R. CAD and the product master model. Computer Aided Design, 1998, 30(11): 905–918
15. Badin J, Monticolo D, Chamoret D, et al. Using the knowledge configuration model to manage knowledge in configuration for

upstream phases of the design process. International Journal on Interactive Design and Manufacturing, 2011, 5: 171

16. Belkadi F, Dremont N, Notin A, et al. A meta-modelling framework for knowledge consistency in collaborative design. Annual Reviews in Control, 2012, 36(2): 346–358
17. Bracewell R, Wallace K, Moss M, et al. Capturing design rationale. Computer Aided Design, 2009, 41(3): 173–186
18. Peng G, Wang H, Zhang H, et al. A collaborative system for capturing and reusing in-context design knowledge with an integrated representation model. Advanced Engineering Informatics, 2017, 33: 314–329
19. Chandrasegaran S K, Ramani K, Sriram R D, et al. The evolution, challenges, and future of knowledge representation in product design systems. Computer Aided Design, 2013, 45(2): 204–228
20. Mistree F, Smith W F, Bras B, et al. Decision-based design: A contemporary paradigm for ship design. Society of Naval Architects and Marine Engineers, 1990, 98: 565–597
21. McMahon C, Liu Y, McAdams D, et al. Ontology-based executable design decision template representation and reuse. Artificial Intelligence for Engineering Design, Analysis and Manufacturing, 2016, 30(4): 390–405
22. Nellippallil A B, Song K N, Goh C H, et al. A goal-oriented, sequential, inverse design method for the horizontal integration of a multistage hot rod rolling system. Journal of Mechanical Design, 2017, 139(3): 031403
23. Vadde S, Allen J K, Mistree F. Compromise decision support problems for hierarchical design involving uncertainty. Computers & Structures, 1994, 52(4): 645–658
24. Hu Y, Rao S S. Game-theory approach for multi-objective optimal design of stationary flat-plate solar collectors. Engineering Optimization, 2009, 41(11): 1017–1035
25. Dhingra A K, Rao S S. A cooperative fuzzy game theoretic approach to multiple objective design optimization. European Journal of Operational Research, 1995, 83(3): 547–567
26. Sunar M, Rao S S. Simultaneous passive and active control design of structures using multiobjective optimization strategies. Computers & Structures, 1993, 48(5): 913–924
27. Rao S S. Game theory approach for multiobjective structural optimization. Computers & Structures, 1987, 25(1): 119–127
28. Badhrinath K, Jagannatha Rao J R. Modeling for concurrent design using game theory formulations. Concurrent Engineering, 1996, 4(4): 389–399
29. Takai S. A game-theoretic model of collaboration in engineering design. Journal of Mechanical Design, 2010, 132(5): 051005
30. Xiao M, Shao X, Gao L, et al. A new methodology for multi-objective multidisciplinary design optimization problems based on game theory. Expert Systems with Applications, 2015, 42(3): 1602–1612
31. Chen L, Li S. A computerized team approach for concurrent product and process design optimization. Computer Aided Design, 2002, 34(1): 57–69
32. Ge Z, Hu Q. Collaboration in R&D activities: Firm-specific decisions. European Journal of Operational Research, 2008, 185(2): 864–883
33. Lewis K, Mistree F. Collaborative, sequential and isolated decisions in design. ASME journal of Mechanical Engineering, 1998, 120(4): 643–652
34. Lewis K, Mistree F. Modeling interactions in multidisciplinary design: A game theoretic approach. AIAA Journal, 1997, 35(8): 1387–1392
35. Montgomery D C. Design and Analysis of Experiments. 8th ed. Wiley, 2012
36. Sambu S. A design for manufacture method for rapid prototyping and rapid tooling. Thesis for the Master's Degree. Atlanta: Georgia Institute of Technology, 2001
37. Gao W, Zhang Y, Ramanujan D, et al. The status, challenges, and future of additive manufacturing in engineering. Computer Aided Design, 2015, 69: 65–89