INTERNATIONAL CONFERENCE ON ENGINEERING DESIGN
ICED 01 GLASGOW, AUGUST 21-23, 2001

DESIGN OF PART FAMILIES FOR RECONFIGURABLE MACHINING SYSTEMS BASED ON MANUFACTURABILITY FEEDBACK

Byungwoo Lee and Kazuhiro Saitou

Keywords: design for manufacture, product families, multi-objective optimization

1 Introduction

Reconfigurable machining system (RMS) is a new class of manufacturing system recently proposed in [1], which aims at combining the high throughput of dedicated manufacturing lines (DML) with the flexibility of flexible manufacturing systems (FMS). An RMS can simultaneously manufacture multiple product types with high throughput comparable to a DML, making it an ideal choice for the high-volume production of product families. A product family manufactured with an RMS, however, requires careful manufacturability evaluation, since even a minor reduction in the unit production cost would result in a large economical benefit due to its high throughput.

Despite the recent attentions form academia and industry, design for manufacturing (DFM) for a product family is still not as mature as its counterpart for a single product. This is partly due to the difficulty in the manufacturability evaluation of product families. Due to the tight sharing of manufacturing resources among multiple product types, a slight change in design feature can have a dramatic impact on the manufacturing cost. The *quantitative* manufacturability evaluation, therefore, is essential for the effective implementation of DFM for product family design.

This paper presents a method for designing a product family for an RMS, using a quantitative manufacturability evaluation based on the simulation of production scenario under a given production plan. A family of machined products, *i.e.*, part family, is considered whose core functions are defined as geometrical relationships among the machined faces. The method evaluates a part family by estimating the cycle time and facility cost necessary for the production, and generates alternative datum definition that would realize a better resource sharing, hence leading to the lower production cost. A case study with a family of L-shaped brackets is given for illustration.

2 Related work

Herrmann and Chincholkar [2] have suggested design for production (DFP) method, where designers can evaluate product designs by comparing their manufacturing requirements with the available production capacity and estimated cycle time. Kusiak and He [3] have suggested four ‘design for agility’ rules for product designs robust against the changes in the characteristics of production schedules. Although these methods suggests the reconsideration of specific design features, it cannot automatically generate redesign suggestions due to the lack of automated reasoning on the design features essential to the product function.

Hayes and Sun [4] developed a knowledge-based system to generate alternative tolerance and datum relationships that reduces setup and processing time, based on the tolerance network of a machined product. The method was successively applied for shape-changing redesign suggestions [5]. Mantripragada and Whitney [6] applied a similar representation, Datum Flow Chain, to an assembled product to evaluate its capability to deliver the intended function. While these work provided the basis of the present work, they do not utilize the quantitative manufacturing feedback to generate redesign suggestions.

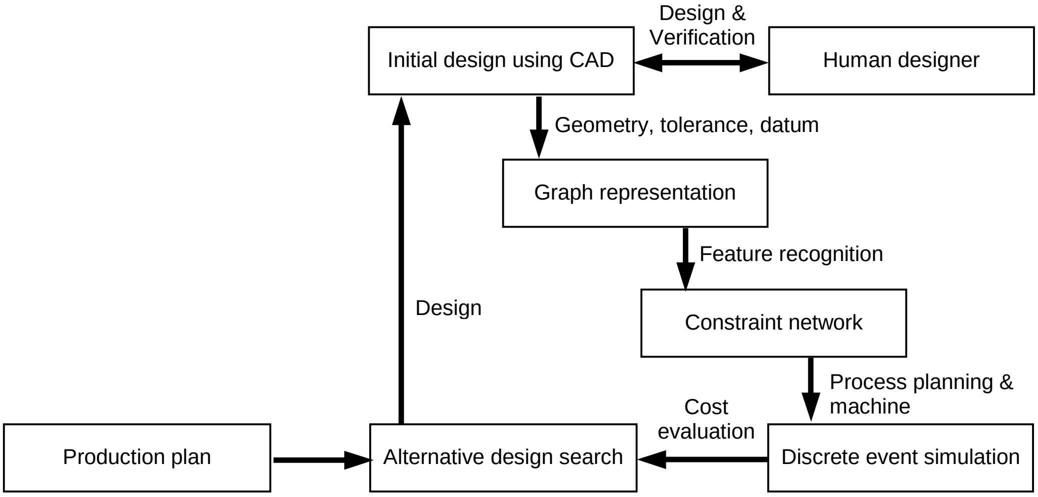


figure 1. the developed method for suggesting alternative designs of a part family based on quantitative manufacturability evaluation.

3 Modeling and problem formulation

A graph-based representation of product geometry and tolerances has been utilized to evaluate and manipulate product designs. It is a modified attributed adjacency graph (AAG) [7], whose nodes and (undirected) edges represent the faces and adjacency of two faces in a product, respectively. The graph also contains directed edges, which represent the tolerance and datum dependencies among the faces. Given an initial design of each product in a family and a production plan (volume ratio of the product mix), the method generates alternative designs realizing lower production and facility costs based on the following steps:

1. **Feature recognition:** Transform the initial designs into the constraint networks among machining features, by extracting the precedence relationships among machining features within the nodes in the AAG representation.

2. **Manufacturing cost estimation:** Based on the process precedence imposed by the constraint networks, estimate the lowest production and facility cost of the product family under a given production plan, by optimizing the configuration of an RMS that simultaneously produces the product family.

3. **Redesign suggestion:** Based on the functional requirements inferred from the constraint networks, find a new network that gives lower production and facility costs than the initial design, in the same fashion as in 2.

A summary of the developed method is illustrated in Figure 1. Details of each step are described in the rest of the section.

3.1 Graph representation of product information

An attributed adjacency graph (AAG) representation similar to previous work [4,5] is adopted to represent geometry and tolerance/datum definitions of products in a family. A node represents the faces (*eg.*, cylindrical or planar) in a product and a undirected edge represents the adjacency between the faces (*eg.*, circular and straight edges). The graph also contains directed edges that represents the dependencies in tolerances and dimensions between two faces (*i.e.*, the definition of datums). Figure 2 shows a simple L-shaped bracket and its graph representation. For instance, the nodes “PF” and “CF” represent planar and cylindrical faces, respectively. Undirected edges “s+” and “c-” represent convex straight and concave circular edges, respectively, and a directed edge “x2” from a node “CF” to another represent a center location of one circular face is defined with respect to another circular face.

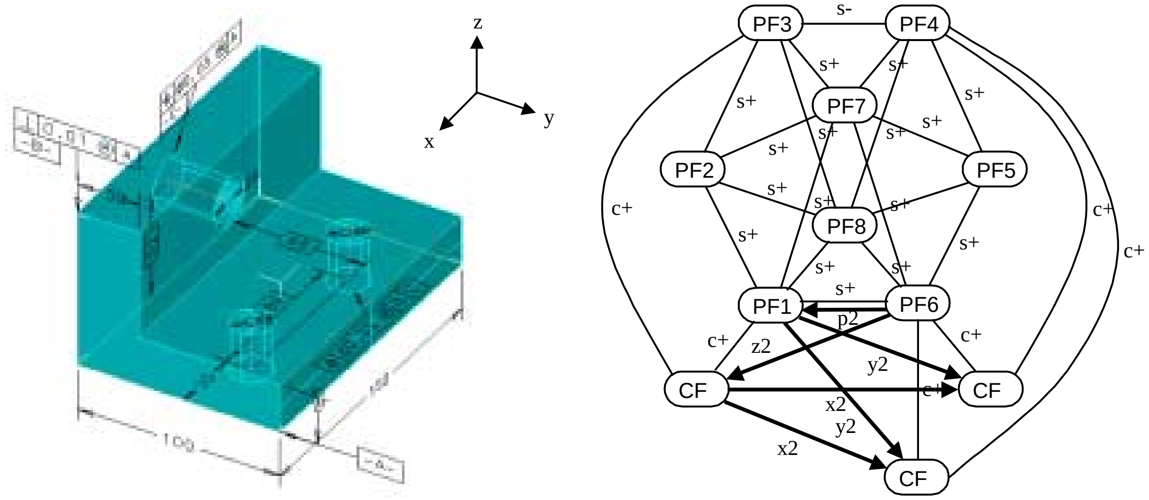
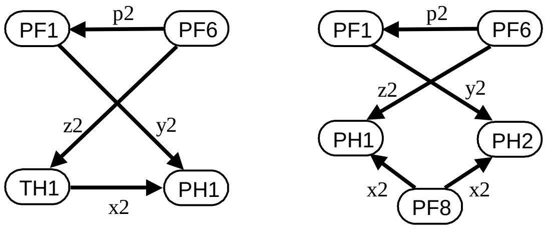


figure 2. CAD model of a product (left) and its AAG representation (right).

3.2 Constraint network after feature recognition

The AAG representation is transformed to a constraint network (CN) among manufacturing features, by deleting the nodes not belonging to any machining features, and aggregating the nodes belonging to a machining feature. A constraint network provides the precedence relations among machining features. A node represents a manufacturing feature and a directed edge represents tolerance and datum information inherited from the corresponding AAG. Attributes of each node include the volume of metal to be removed, orientation of tool approach and type of feature for the process planning. Figure 3 (a) and (b) show, respectively, the CN’s constructed from the product in figure 2 and its variant discussed in the case study.



(a) (b)

figure 3. constraint networks of (a) product in figure 2, and (b) its variant with an additional hole.

3.3 Modeling of process planning, manufacturing system configuration and firing sequence

The process plan specifies a sequence of manufacturing features, which satisfies the precedence conditions represented in the constraint network. In order to build manufacturing system configuration, we also need to decide allocation of manufacturing features to machine stations, which can be described by a correspondence between manufacturing features and machine stations. The process plan can be summarized as a vector **p,** which includes every node $f \in F$ as its component without duplication. And machine allocation can be represented as a correspondence $Corr : F \mapsto S$, where *F* is a set of manufacturing features from CN and *S* is a set of machines available. A *Corr* assigns a manufacturing feature $f \in F$ to a matching type of machine $s \in S$, according to attribute of *f* and *s*. For example, it will assign a through hole to drilling machine but not to a milling machine. It is assumes that a process is assigned to a unique machine. In other words, one-to-many correspondence is not allowed. This implies that a product is allowed to pass the manufacturing system via a unique route.

When process plans and machine allocation is decided, we can build a manufacturing system configuration by linking machines and assigning attributes to them. The manufacturing system configuration is defined as a four-tuple: *Config(***p***, Corr)=(S, E, Am, Ae),* where *S* is the set of nodes, *E* is the set of directed edges, *As* is the set of attributes to node *S*, and *Ae* is the set of attributes to directed edge *E,* in which a node represents a machine station and a directed edge represents transfer line. The attribute of a node – a machine station represents the type of machine such as face milling or drilling. The attribute of an edge represents the type of product that is supposed to be transferred through the edge. Since there is no buffer assumed between machine stations, a product is not allowed to visit a machine that it have already visited once, to avoid system's deadlock. For the same reason, no scheduling rule is necessary except for firing sequences, denoted by vector **s,** at the start buffer of the manufacturing system. The firing sequence is the order of types of products with a certain length, which are waiting for entering a machine.

3.4 Discrete event simulation for the evaluation of cycle time

When process plans, manufacturing system configuration and firing sequence are decided, a discrete event simulation is run to estimate the average cycle time. The average cycle time is defined as the average time span spent to obtain a completed product after obtaining previous one. The processing time of a machining feature is estimated by the volume of material removal divided by material removal rate of the corresponding machine, plus setup time if the orientation of tool approach is different from that of the previous operation. When the computed time is passed at a particular machine station and the next station to visit is empty, the product is delivered to the next station. Time is measured from when a product arrives the final buffer for the first time, to when the number of products contained in the final buffer reaches the specified sequence cycle. Then the measure time is divided by the sequence cycle to obtain the average cycle time t_c.

3.5 Simultaneous optimization of process planning, manufacturing system configuration, and firing sequence

We consider a scenario where a manufacturing system simultaneously produces multiple types of products, which shares some of their processes of similar size. Production plan for a given period of time is specified as the fraction of each type of products. Let *n* be the number of types of the products and the fraction be α_i, where $0 \le \alpha_i \le N$ for i=1,2,..,n and $\sum_{i=1}^{n} \alpha_i = N$ for some constant N, or collectively be a n dimensional vector **a**. Therefore, a production plan can defined as a function of the fraction vector **a**, which we shall call $\rho(\mathbf{a})$.

For a given set of two or more product designs and production planning for a time period, the system searches for the best process planning for each product, manufacturing system configuration and firing sequence to obtain the minimal cycle time and facility cost. Our objective is to minimize facility cost while achieving efficient production. Facility cost including running cost of machines is assumed only dependent on number of machines. Efficient production can be also simply represented as minimal cycle time. Hence, overall cost estimation for production of a product family for a production plan can be estimated as the summation of the number of machines $|S|$ and the average cycle time t_c weighted by a set of constants. This simultaneous optimization problem can be summarized as follows:

For given : set of constraint network CN_i, i=1,2,..,n (1)
production plan $\rho(\mathbf{a})$, and
length of firing sequence $|\mathbf{s}|$,

find : process planning **p,**
correspondence $Corr : F \mapsto S$, and
manufacturing system configuration *Config(***p**, *Corr),*
firing sequence **s**

which minimize : overall-cost= $w_p \times t_c + w_f \times |S|$,
where w_p and w_f are weights

3.6 Redesign suggestion

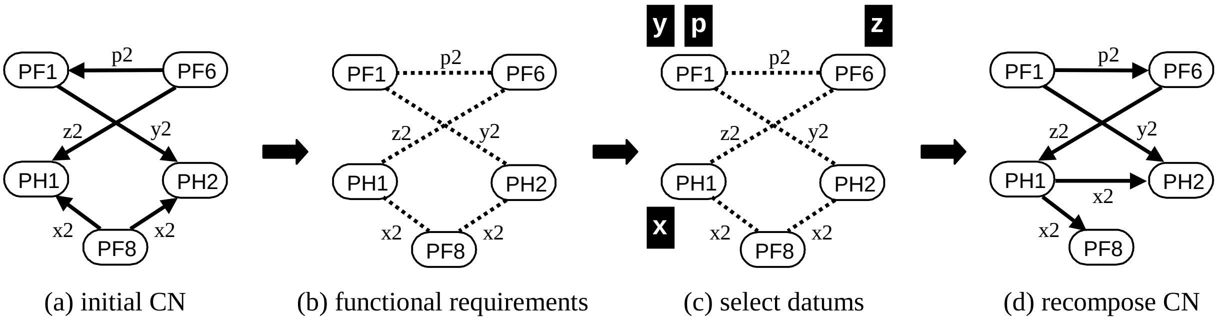
So far, the discussion has been on the evaluation of cycle time for given multiple product designs. This section will describe how to generate alternative designs that give better cycle time, based on the framework illustrated in figure 1. The functional requirements of machined parts are often achieved by the tolerance relationship of features. For example, if some two products are assembled using holes of the bracket shown in figure 2 and if their relative location in x-direction is important, relative location of two holes of the bracket must be kept precise, which means necessity of tight tolerance among the holes. When initial designs are provided, we assume that all tolerance relationships are indispensable for functional requirements. And alternative designs are searched in a range that does not break functional requirements. The system searches possible alternative datums based on following sequence (see figure 4).

1. The functional requirements (figure 4 (b)) are extracted from the initial CN (figure 4 (a)), where a dashed line means there exists a path with the designated attribute, between two nodes connected by it, or there exists another node other than two nodes from which paths to two nodes exist.

2. The system randomly selects only one manufacturing feature (a node in CN) for one type of geometry tolerance (figure 4 (c)). For example, in a prismatic part, the positional tolerances in x-direction may have one planar face as the only datum whose normal vector

is parallel to x-axis. This rule is reasonable and conventional for typical parts, if they are not highly complicated.

3. The system recomposes the CN to be consistent with functional requirements and datums selected.



(a) initial CN (b) functional requirements (c) select datums (d) recompose CN

figure 4. steps to generate alternative designs.

Then, the generated CNs are checked to guarantee all features within the CN are well constrained in terms of tolerance. Although representation is slightly different, the abstract of rules adopted below can be found in Tsai and Cutkosky [8] in depth.

- A loop is not allowed in a *CN*. Loops that consist of only one node are exceptions and processed as self-reference tolerances (*eg.*, flatness).

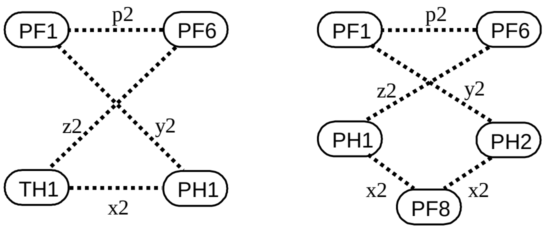
- A node is not allowed to have more than one incoming edge with same type of tolerance. Otherwise, the feature is over-constrained or one of the incoming edge is redundant.

Due to the high complexity of the problem, a multi-stage optimization scheme utilizing genetic algorithm ([9], [10]) is adopted. At the top of the scheme, the candidate CNs generated are checked if they meet rules described above. When they meet the rules, they are passed into the next stage where the routine in equation (1) is initiated. At this stage, if there is no loop detected, candidate pairs of a process planning and a manufacturing system configuration are passed into the final stage where the firing sequence with minimum average cycle time is decided through the discrete event simulation system. Since this scheme excludes infeasible solutions step by step without running whole procedure for every candidate solution, it allows a faster evaluation.

4 Examples

In this section, we provide a simple case study to show effectiveness of the method described above, with simulation result. A set of alternative designs for two products (i=2) are suggested at the end of result such that they are the most cost-effective for particular production plans. The initial CAD model and graph representation of one of two products, part A, are depicted in figure 2. Those for part B is omitted due to limitation of space allowed, but the CNs of part *A* and *B* can be found in figure 3, in which datum definitions for two products are quite similar except for position tolerance of two holes in x-axis direction. This resemblance comes from common design practice that is, when more than two similar designs launched together or when one product is designed after the other, datum definitions for them are similar to reduce cost for production plan changes and to utilize existing fixtures.

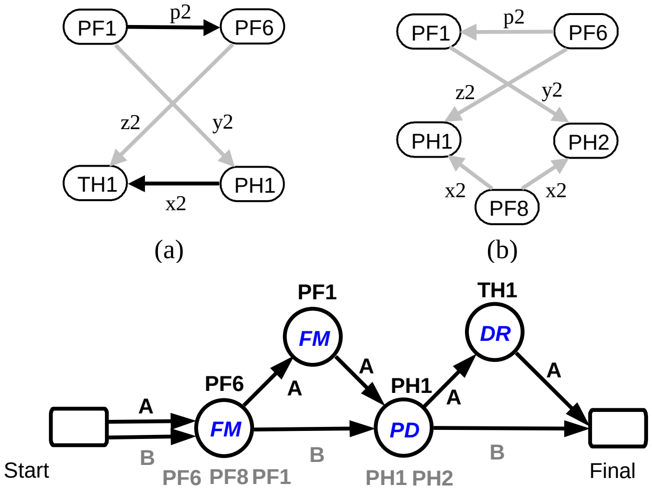
All manufacturing features and tolerances for them are assumed to be essential to fulfill functional requirements. Then, functional requirements for two product can be described as two graphs with dashed edges in figure 5.



(a) (b)

figure 5. (a) representation of functional requirements for product A and (b) product B.

A set of optimized CNs for two products, a *Config* and accompanying process plannings obtained after running the system is presented in figure 6 for production plan of **a**=(9,1). In the CNs, suggested redesign is represented as black edges. In product A, the directions of two edges are reversed. Although the number of the required setups is the same as the original design, the new design has a shorter cycle time due to the better resource sharing by having "PD" prior to "DR." We can also observe that the manufacturing system is configured mainly for part A, with occupies four machines, while part B does only two, which is reasonable when we consider the production plan of **a**=(9,1). The original design of each product is updated according to suggested redesign and supposed to be verified by a human designer.



(a) (b) (c)

figure 6. (a) suggested redesign of product A and (b) product B, and (c) configuration of the RMS optimal for production plan **a**=(9,1).

5 Conclusion and future work

The above case study demonstrated that the developed method can successfully identify an alternative tolerance and datum relationships to realize shorter cycle time and lower facility cost under a given production plan. Although not included in the paper, it has been observed that the resulting redesign suggestions would greatly vary depending on the given production plans, indicating the importance of the quantitative manufacturability evaluation including production plans. Future work includes the extension of the proposed framework to design product families whose production cost is insensitive to the changes in production plans due to market demand fluctuations. Also, faster and more accurate estimation of cycle time would enhance the applicability of the proposed method to more complex products.

6 Acknowledgments

We gratefully acknowledge the financial support from the Engineering Research Center for Reconfigurable Machining Systems, established by National Science Foundation.

References

[1] Koren, Y., Hiesel, U., Jovane, F., Moriwaki, T., Pritschow, G., Ulsoy, G. and Van Brussel, H., “Reconfigurable manufacturing systems,” Annals of the CIRP Vol. 48, no. 2, 1999, pp. 1-14.

[2] Herrmann, J.W. and Chincholkar, M.M., “Design for production: a tool for reducing manufacturing cycle time”, ASME Design Engineering Technical Conferences, Las Vegas, Nevada, 2000, Paper No. DETC2000/DFM-14002

[3] Kusiak, A. and He, D.W., “Design for agility: a scheduling perspective,” Robotics and Computer-Integrated Manufacturing, Vol.14, 1998, pp. 415-427.

[4] Hayes, C.C. and Sun, H.C., “Using a manufacturing constraint network to identify cost-critical areas of designs,” Artificial Intelligence for Engineering Design, Analysis and Manufacturing, Vol. 9, 1995, pp. 73-87.

[5] Hayes, C.C., “Plan-based manufacturability analysis and generation of shape-changing redesign suggestions,” Journal of Intelligent Manufacturing, Vol. 7, 1996, pp. 121-132.

[6] Mantripragada, R., Whitney, D.E., “The datum flow chain: a systematic approach to assembly design and modeling”, ASME Design Engineering Technical Conferences, Atlanta, GA, 1998, Paper No. DETC98/DFM-5713

[7] Joshi, S. and Chang, T.C., “Graph-based heuristics for recognition of machined features from a 3-D solid model”, Computer-Aided Design, Vol. 2, no. 2, 1988, pp. 58-66.

[8] Tsai, J. and Cutkosky, M.R., “Representation and reasoning of geometric tolerances in design”, Artificial Intelligence for Engineering Design, Analysis and Manufacturing, Vol. 11, 1997, pp. 325-341.

[9] Goldberg, D.E., Genetic Algorithms in Search, Optimization and Machine Learning, Addison-Wesley, 1989

[10] Holland, J.H., Adaptation in Natural and Artificial Systems, The University of Michigan Press, Ann Arbor, Michigan, 1975

Kazuhiro Saitou
The University of Michigan, Department of Mechanical Engineering, 3211 EECS, 2350 Hayward St., Ann Arbor, Michigan, 48109-2125, USA, Tel: +1-734-763-0036, Fax: +1-734-647-3170, E-mail: kazu@umich.edu, URL: http://www.personal.engin.umich.edu/~kazu