Proceedings of DETC'01
2001 ASME Design Engineering Technical Conferences
September 9-12, 2001, Pittsburgh, Pennsylvania

DETC01/DAC-21121

DECOMPOSITION-BASED ASSEMBLY SYNTHESIS FOR MAXIMUM STRUCTURAL STRENGTH AND MODULARITY

Onur L. Cetin and **Kazuhiro Saitou**[*]
Department of Mechanical Engineering
University of Michigan
Ann Arbor, MI 48100-2125, USA
E-mail: {ocetin, kazu}@engin.umich.edu

ABSTRACT

This study presents a systematic decomposition process to carry out assembly synthesis as a tool during the conceptual design phase of a product. Two configurations obtained by structural topology optimization are decomposed automatically into assemblies consisting of multiple members with simpler geometries. The optimal decomposition can be posed as a graph partitioning problem, which is actually a discrete optimization task. Considering the nonlinearity and the corresponding computational overhead of the problem, a steady-state genetic algorithm is employed as the optimization method. The final objective function attempts to find a solution that brings about two structures with maximum structural strength, maximum assemblability, and one or more components that can be shared by both products. The software implementation is carried out and a typical problem is solved using the procedure. It is observed that the algorithm manages to find an acceptable solution, allowing the commonality of one component in both end products and still maintaining a good structural strength and assemblability.

KEYWORDS

Design for assembly, modularity, discrete design optimization, structural optimization, genetic algorithms.

INTRODUCTION

Product design is a process in which many product attributes such as cost, performance, manufacturability, safety, and consumer appeal are considered together. Thus, in virtually all cases, designers are forced to make trade-offs among competing criteria. At each stage of the design cycle, solutions are evaluated and reevaluated in the light of a diverse ensemble of objectives.

The time and cost involved in making engineering changes, in-process adjustments and the like increase rapidly as the product development process evolves. Early anticipation and avoidance of manufacturing and assembly problems can have a huge impact in reducing the product development time (Mantripragada and Whitney, 1998).

Most structural products are manufactured through assembly of various components which have simpler geometries than the end product. The decision of which components are better to assemble together to achieve a certain end product is defined as *assembly synthesis* (Saitou and Yetis, 2000). Since assembly is typically the final manufacturing process, it can bring to light problems that arise at earlier stages in the manufacturing system (Smith, 1998).

During conceptual design, teams of designers generally begin to develop a new product by sketching its general shape on paper. This "back of the envelope" approach is key aspect of the creative thought process. As a tool for the engineers during

---

[*] Corresponding author

this brain-storming period, this project, based on the earlier work in the Discrete Design Optimization Laboratory at the University of Michigan (Saitou and Yetis, 2000), aims to achieve a systematic decomposition process to carry out assembly synthesis. The presented approach intends to provide the designer with feedback about possible decompositions prior to the detailed design phase. The main contribution of our research to the existing method is that, now the developed software is capable of evaluating several design problems simultaneously to end up with maximum modularity of the end products, in addition to the optimization of structural strength and assemblability in each design.

PREVIOUS WORK

The method we propose to carry out assembly synthesis has some common roots with assembly sequence planning applications, which has been an active research field recently.

In most of the solutions for assembly sequence generation, the geometric model of an assembly is created by describing the components and the spatial relationship among them (Eng *et al.*, 1999). In recent years, features that combine geometric and functional information have been introduced in modeling and planning for manufacturing of parts. An integrated object-oriented product model is introduced by van Holland and Bronsvoort for modeling and planning of both single parts and assemblies (van Holland and Bronsvoort, 2000). Wang and Bourne describes an integrated system for the design and production of sheet metal parts. They automatically generate some features for the sheet metal bending process as the design progresses. After the designs are complete, an automatic process planning system uses the features and generates new ones to aid the production of plans with near-minimum manufacturing costs (Wang and Bourne, 1997).

Most algorithms cited in the literature solve assembly problems by graph searching. Each joining of a component to another component or to a subassembly is called a *liaison*. The general approach is building a liaison diagram and generating all possible subassemblies by decomposing the graph (also called “cut-set” algorithms). Then the possible assembly sequences are evaluated based on the given constraints to determine the most suitable one (Mantripragada and Whitney, 1998; Whitney *et al.*, 1999). Such an exhaustive searching method requires substantial computational resources even for a simple structure. As a computational tool, genetic algorithms (GAs) have proved successful in solving combinatorial and complex problems, such as finding a near-optimal assembly plan, with a reasonable execution time (Senin *et al.*, 2000; Lazzerini and Marcelloni, 2000).

In addition to the structural strength and assemblability criteria incorporated in the objective function in assembly synthesis, which was tested and verified in the earlier work (Saitou and Yetis, 2000), a measure of modularity is evaluated in this study.

Modularity is commonly associated with the division of products into smaller building block, *modules*, and involves architecting a family of products that share inter-changeable components. The benefit of part commonality is that, the effort and resources invested for the design of one module are not considered again, if the component fits another product. Modularity not only enables simultaneous work in the product development, but the manufacturing process may also be performed in parallel, so lead-times can be reduced (Stake, 1999).

Ishii reports that modularity in product design impacts every stage of the product life-cycle, as wells as affecting serviceability and recyclability in terms of disassembly, separation, repair, and reprocessing. He introduces a set of metrics and design charts that aid in enhancing life-cycle modularity of product families and generations (Ishii, 1998). Newcomb *et al.* developed a method employing a commonality table for the entire product family to identify the effects of a product platform. They determine the commonality indices for the different members of the family for different viewpoints and then combine the measures for the members of the product family to achieve an overall platform index (Newcomb *et al.*, 1998). Kota *et al.* follow a similar approach and present an objective measure called the Product Line Commonality Index, to capture the level of component commonality in a product family. They suggest seeking functional design features based on configuration similarities (e.g. geometric shapes), kinematic similarities (e.g. joint types and motion), actuation similarities and the like (Kota *et al.*, 2000). In addition to product driven concerns, Yu *et al.* introduce a customer need basis for defining the architecture of a portfolio of products (Yu *et al.*, 1999). To study modularity based design decisions quantitatively, a multicriteria optimization problem is formulated by Nelson *et al.*; they analyze Pareto sets that correspond to various derivative products to develop a systematic product platform design methodology (Nelson *et al.*, 1999).

ASSEMBLY SYNTHESIS METHOD

Although proven to be effective, the approaches in the assembly planning literature require detailed component geometry as input, hence limiting their application to early phases of the design process; it is aimed to overcome this limitation in this project.

In the current approach, a structure obtained via structural topology optimization is decomposed automatically into an assembly consisting of multiple structural members with simpler geometries. There are two main steps in the process developed:

1. A two-dimensional bitmap image of a structure obtained via structural topology optimization is transformed to a product topology graph through application of image processing algorithms.

2. The product topology graph is decomposed into subgraphs by using a genetic algorithm which results in a decomposition of the product with chosen mating features.

The optimal decomposition can be posed as a graph partitioning problem, which is considered a discrete optimization task. The members of the structure are mapped to nodes and the intersections are mapped to multiple edges since they can be joining more than two members. The problem can be defined as: given the topology graph of the structure, obtain the partition representing the optimal decomposition and the mating feature for each joint, subject to a cost function evaluating the decomposition quality.

The objective function to evaluate each decomposition can be chosen in the light of the guidelines for Design of Manufacturing (DFM) and Design for Assembly (DFA) methods in the literature. Typical examples are (van Vliet *et al.*, 1999):

- Maximize standardization (materials, design concepts, components, tools, fixtures, modular design)
- Select solutions that simplify manufacturing (shape, composition etc.)
- Choose solutions that enhance uniformity and parallelism
- Minimize the number of required resources

In our approach, to evaluate the decomposition according to the structural strength criteria, the normal stress at the joints and the area on which the normal stress acts are calculated. The evaluation is based on the difference between the angle at which the normal stress is minimum (θ_{ideal}) and the chosen mating angle; note that deviation from the ideal angle means higher normal stress.

It is decided that joining method at every joint is assigned as spot weld in the current problem and the only joint feature considered is the weld angle which is chosen from discrete set of possible values. Welding orientation is an important factor in the design and manufacturing of weld products. Welding orientation selection must be made at the early stages of the design process so that necessary design changes can easily be made to achieve an optimal design solution; consequently other design tasks, such as fixture design, can be completed in parallel (Yao *et al.*, 1998).

When assemblability is considered, the similarity of weld angles and the number of welds in the decomposition are taken into account. Obviously, lower number of welds and similar weld angles result in higher assemblability.

The modularity criteria proposed in this work is implemented by analyzing two structures at a time, and assessing the similarity of the disconnected components to point at a probable part commonality. A term is added to the objective function to favor the decompositions that result at: a) components with similar stress states, represented by the joint angles, b) components that are geometrically similar to each other, by considering the lengths and thicknesses of their corresponding members, or by using an equivalent measure of shape similarity. Also, before evaluating the cost function component related to modularity, it is certified that the subgraphs of the components to be shared are *isomorphic*; note that this is a necessary but not sufficient condition for two structures to be assembled in the same way.

Thus the final objective function attempts to find a solution that brings about two structures with maximum structural strength, maximum assemblability, and one or more components that can be shared by the both designs. In this project, the assembly synthesis method will be tested by using two structural design problems, as given in Figure 1: note that the only difference between (a) and (b) is the application point of the concentrated force P.

(a) Design problem 1 (b) Design problem 2

Figure 1: The design problems to be addressed simultaneously

Carrying out the structural topology optimization process[1] for the loadings given in Figure 1, and aiming to achieve a structure with maximum stiffness using %40 of the volume in the design domain, the topologies presented in Figure 2 are obtained. So the problem becomes finding two optimal decompositions for Figure 2a and 2b so that maximum structural strength for both structures are maintained, and at the same time some components are shared by the products.

(a) Topology for problem 1 (b) Topology for problem 2

Figure 2: Optimum topologies for the design problems

MATHEMATICAL MODEL

Definition of the design variables

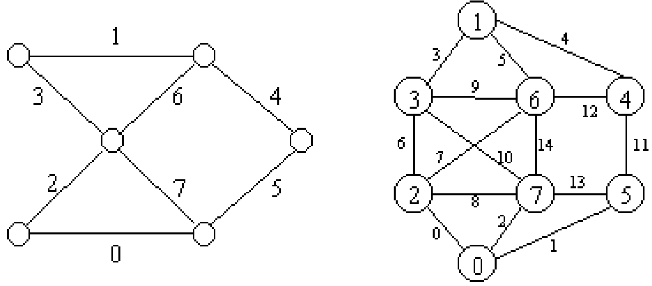
Let the members of the structure be mapped to the nodes of the product topology graph and the intersections be mapped to the edges[2]. The graph representation for the optimum topology of the first design problem is given in Figure 3 as an example. So the whole structure can be represented as $G=(V, E)$ with a node set V and an edge set E. The problem of optimal decomposition becomes one of finding a partition, *i.e.* the

---

[1] Topology optimization website at the Technical University of Denmark (http://www.topopt.dtu.dk) is used.

[2] LEDA library developed at the Max-Planck Institute of Computer Science (http://www.mpi-sb.mpg.de/LEDA/) is used for the graph algorithms.

design variable *P*, of the node set *V* such that the objective function, c*(P)*, is maximized.



(a) Simplified topology (b) Corresponding graph

Figure 3: Graph representation for problem 1

Mating features at the joints are to be used to assess the structural strength of the members: therefore a set, *F*, of joint features must be defined to be able to evaluate different decompositions. Based on assumptions in the earlier work, *F* is the set of possible mating angles at the welded joints.

The optimal partitioning of *G* can be represented mathematically by a vector $=(x_i)$ where x_i is a binary variable representing the presence of edge e_i in the decomposition defined by the partitioning *P*. It is obvious that i=*1,…,|E|* since there are |E| edges in the topology graph. Another vector $=(y_i)$ is defined to store the mating features for each edge e_i; note that domain of **y** depends on the model of the joint represented by the edge.

Definition of the constraints

The constraint on the vector , which represents the presence of edges, is the following:

$$\text{COMPONENTS}(\text{GRAPH}(\ )) = k \tag{1}$$

where

- GRAPH( ) returns the graph after the edges with $x_i = 0$ in vector *x*, have been removed from the original topology graph,
- COMPONENTS(G) returns the number of disconnected components in graph G,
- k denotes the desired number of components specified by the user.

The constraint on vector **y** is as follows:

$$y_i \in F \tag{2}$$

where *F* is the set of mating angles at which spot welds can be applied at the joints. One element of set *F* represents the case for no weld at the corresponding joint.

Another constraint is imposed on the combination of the vectors and in the following way:

$$\text{IS\_CONNECTED}(\text{COMBINED\_GRAPH}(\ ,\ )) = 1 \tag{3}$$

where

- IS_CONNECTED(G) is a function which returns 1 if the graph G is connected and returns 0 otherwise.
- COMBINED_GRAPH(,) is a function that returns a graph which consists of the nodes of the original graph and the edges in vectors , . This constraint ensures that the combination of the decomposition given by vector and the mating angles given by vector constitutes a structure which has the same connectivity as the original disconnected structure.

Definition of the objective function

Objective function will evaluate each decomposition according to the following criteria:

- Reduction of structural strength due to introduction of joints
- Assemblability of the decomposed structures
- The maximum modularity of the structures

To evaluate the decomposition according to the structural strength criteria, the normal stress at the joints and the area on which the normal stress acts are calculated. The evaluation is based on the difference between the angle at which the normal stress is minimum, θ_i^{ideal}, and the chosen welding angle given by vector , as deviation from the ideal angle means higher normal stress. The stress at the chosen angle multiplied by the weld area provides a measure of force acting on the weld which is also used in evaluating the decrease in strength. A weld with larger area introduces a higher amount of decrease in strength than a weld with smaller area.

While assessing the decomposition with respect to the assemblability criteria, the similarity of weld angles and the number of welds in the decomposition are taken into account. Obviously, lower number of welds and similar weld angles result in higher assemblability.

These criteria result in the following objective function component for structural considerations:

$$f_S(x,y) = w_1 \sum_{i=1}^{N_{welds}} \left(\theta_i - \theta_i^{ideal}\right)^2 + w_2 \sum_{i=1}^{N_{welds}} \left(\sigma_i(\theta_i) A_i(\theta_i)\right) + w_3 \sum_{i=1}^{N_{welds}} \sum_{j=i+1}^{N_{welds}} \left(\theta_i - \theta_j\right)^2 + w_4 N_{welds} \tag{4}$$

The variables are defined as follows:

$=(x_i)$	x_i is a binary variable representing the presence of edge e_i in subset *x*
$=(y_i)$	y_i is discrete variable representing the choice of weld angle at joint i
w_i	weight of ith criteria in the objective function

N_{welds}	total number of welds in the decomposed structure
θ_i	weld angle with respect to vertical direction at joint i
θ_i^{ideal}	angle of minimum normal stress at joint i
$\sigma_i(\theta_i)$	normal stress at joint i at angle θ_i
$A_i(\theta_i)$	weld area at joint i (function of θ_i)

As the second part of the objective function, the cost function for modularity is incorporated to evaluate two attributes of the components to be shared between the structures:

1. Similarity in stresses that the components are subject to: this condition is simply implemented by maintaining that joint angles of the components should be close to each other,

2. Similarity in shapes of the components in a given (user-specified) tolerance: this attribute is checked by comparing the components with respect to their areas.

Note that this procedure requires that all components that come out of the decomposition process of one structure be compared with the components in the second design problem. However, probably only a few of the components at each iteration will have the same number of members assembled in a similar manner. Thus, before evaluating how similar two components are, it is convenient to test if the corresponding subgraphs are *isomorphic*: the modularity cost function should return a large number if no components are found to be *isomorphic*, and if this check is passed, then the similarity measure can be applied. Considering the computational overhead of this check, a simple approximation, actually a necessary but not sufficient condition is utilized in the software: it is required that the components have an equal number of nodes and edges to be shared. A fast *graph isomorphism* check algorithm will be employed for more complex design problems in the future work.

Thus the modularity component of the objective function is defined conditionally to be:

$$f_m(x_1,y_1,x_2,y_2)=\begin{cases}\textbf{if } \text{Is\_Isomorphic}(g_1,g_2)=\text{FALSE}, \\ \textbf{return } (\text{a large number}). \\ \\ \textbf{if } \text{Is\_Isomorphic}(g_1,g_2)=\text{TRUE}, \\ \textbf{return } w_5\displaystyle\sum_{i=1}^{N^c{}_{welds}}((\theta_1)_i-(\theta_2)_i)^2+w_6 h(g_1,g_2).\end{cases} \tag{5}$$

where

- g_1 and g_2 are two subgraphs representing components resulting from the decomposition of structure 1 and structure 2 respectively,
- w_5 and w_6 are the weights for the corresponding criteria,
- $(\theta_1)_i$ and $(\theta_2)_i$ are the weld angles at joint i of each component,
- $N^c{}_{welds}$ is the number of welds in the shared components,
- Is_Isomorphic(g_1,g_2) is a function that returns TRUE if subgraphs g_1,g_2 are *isomorphic*, FALSE otherwise. For the time being the function only checks if the two subgraphs have the same number of nodes and edges.
- h(g_1,g_2) is a function that returns a measure of geometric similarity between the components. This measure is realized by the calculation of first moments of component areas with respect to origin; so the locations of the components in the configuration are also incorporated.

Note that before $f_m(\ _1,\ _1,\ _2,\ _2)$ returns a cost at an iteration, all components, i.e. all subgraphs are examined, and only if none of them are *isomorphic* a large number is returned to introduce a penalty for lack of part commonality. In a similar manner, if more than one component in each structure match with others, the similarity measures are added up to favor the sharing of several components among the products.

The constraints and objective function combine to give the following optimization problem:

minimize $f(\ _1,\ _1,\ _2,\ _2) = f_s(\ _1,\ _1) + f_s(\ _2,\ _2) + f_m(\ _1,\ _1,\ _2,\ _2)$
subject to
$(x_1)_i \in \{0,1\}$, $i = 1, \ldots, |E_1|$
$(x_2)_i \in \{0,1\}$, $i = 1, \ldots, |E_2|$
$(y_1)_i \in F$, $i = 1, \ldots, |E_1|$
$(y_2)_i \in F$, $i = 1, \ldots, |E_2|$
COMPONENTS(GRAPH(x_1)) = k_1
COMPONENTS(GRAPH(x_2)) = k_2
IS_CONNECTED(COMBINED_GRAPH(x_1,y_1)) = 1
IS_CONNECTED(COMBINED_GRAPH(x_2,y_2)) = 1

OPTIMIZATION METHOD

As reported by Yetis and Saitou (Saitou and Yetis, 2000), exact solution of the graph partitioning problem requires exponential computation. Noting the computational overhead, and taking into account the high non-linearity of the cost function as well, genetic algorithms (GA), which are regarded as a compromise between random and informed search methods, and which have proved very efficient in the solution of discrete optimization problems, is conveniently used in this project.

The decomposition problem is to be solved by using a steady-state GA. The basic flow of the algorithm is as follows:

1. Randomly create a population P of n chromosomes (an encoded representation of design parameters and) and evaluate their fitness values and store the best chromosome. Also create an empty subpopulation Q.

2. Select two chromosomes c_i and c_j in P with probability

$$\text{Prob(chromosome } c_i \text{ is selected)} = \frac{f_i}{\sum_{k=0}^{n} f_k}$$

where f_i is the fitness value of chromosome c_i.

3. Crossover c_i and c_j to generate two new chromosomes c_i' and c_j'.
4. Mutate c_i' and c_j' with a certain low probability.
5. Evaluate the fitness values of c_i' and c_j' and add them in Q. If Q contains less than m new chromosomes, go to 2.
6. Replace m chromosomes in P with the ones in Q and empty Q. Update the best chromosome and increment the generation counter. If the generation counter has reached a pre-specified number, terminate the process and return the best chromosome. Otherwise go to 2.

Empirical advantages of steady-state GA are that it prevents premature convergence of population and reaches an optimal solution with fewer number of fitness evaluations (Saitou and Yetis, 2000).

Each solution is encoded in a chromosome in the following way: The chromosome is of length 2|E| where |E| is the number of the edges in the graph. First |E| genes carry binary information about which edges of the topology graph are kept and which are removed to produce a decomposition (Figure 4). If the i^{th} element of the chromosome is 0, it means that this edge has been cut in this particular decomposition represented by this chromosome.

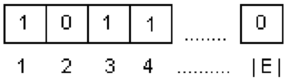


Figure 4: First half of chromosome with binary information

The second half of the chromosome carries the information about which discrete choice of possible mating angles is chosen for a given joint (Figure 5). The $(|E|+i)^{th}$ element carries the choice of mating angle for the i^{th} joint(edge in the graph).

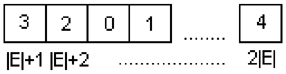


Figure 5: Second half of chromosome with mating angle information

Since the procedure introduced in this project requires the simultaneous evaluation of two structures, apparently the chromosomes given in Figures 4 and 5 cannot be used on their own. A simple way of examining two chromosomes, i.e. two partitioning problems at once is combining the chromosomes and treating the genome properly by customized crossover and mutation operations. Then the length of the chromosome becomes $2|E_1| + 2|E_2|$, where E_1 and E_2 represent the number of edges in each structure's topology graph. Since the customization of the operations and representations given in this section for this new application only involves the repetition of the tasks for both 1st and 2nd structures, and the implementation consists of solely changing the indexes to point to the correct gene, details are avoided in this paper.

For this study, the possible mating angles have been chosen as –45, 0, 45, 90 degrees from the vertical and map to gene values of 1, 2, 3, 4, respectively. A gene value of zero means no weld at that intersection.

Since chromosomes representing the decompositions carry two different kinds of information (x_i is binary and $y_i \in F$) the cross-over and the mutation operators have been customized. The crossover operator treats the first and second halves of the chromosome simultaneously since the information in the second half complements the information in the second half and only combinations of corresponding genes in the first and second halves represent a good or bad solution. Therefore application of crossover at the same point in both halves preserves the good or bad nature of the chromosome. Practically the custom crossover operator is a multi-point crossover operator (Figure 6).

As genetic algorithms do not handle constraints directly, the constraints in the mathematical problem formulation have to be translated into penalty terms. Therefore, the fitness function will consist of two main terms; the objective function value f($_1$, $_1$, $_2$, $_2$) of the decomposition and the penalty term which imposes the constraints of the mathematical model:

$$\text{Fitness} = f(\ _1,\ _1,\ _2,\ _2) + \text{Penalty terms} \tag{6}$$

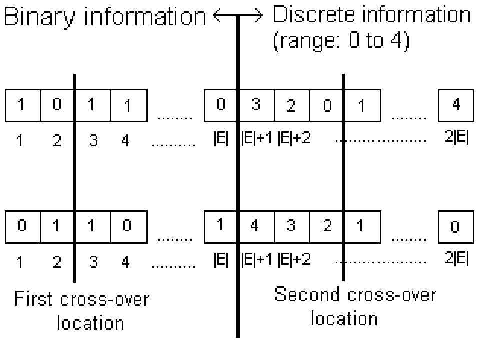


Figure 6: Crossover of two chromosomes

The constraint on vectors and are imposed simply by the chromosome representation of the problem, *i.e.*, genes in the first half of the chromosome are binary values imposing the constraint $x_i \in \{0, 1\}$ and genes in the second half of the chromosome can only have values imposing the condition $y_i \in F$, where F is the set of possible mating angles.

The constraint on the number of components is imposed as a penalty term in the fitness function by taking the difference of the resulting number of components and the one specified by the user.

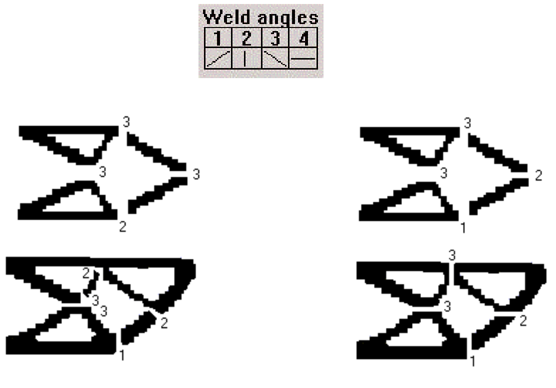
$$\text{Penalty} = (\text{COMPONENTS}(\text{GRAPH}(\ )) - k)^2 \qquad (7)$$

Connectivity constraint is implemented by returning a fitness of infinity (very large number in the software implementation) for decompositions lacking connectivity, *i.e.*, returning 0 when passed to the IS_CONNECTED(G) function. Structurally disconnected decompositions, which are not feasible, are eliminated by this constraint straight away.

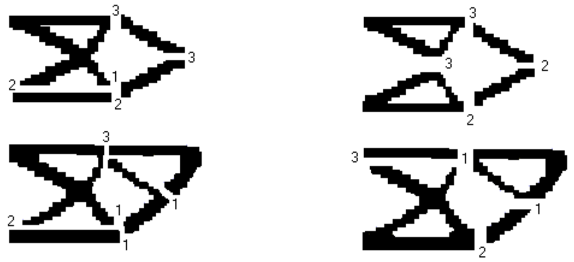
OPTIMIZATION RESULTS

Using a population ranging between 200 and 300 members, and running the genetic algorithm with a termination condition of 5000 to 10,000 iterations, several local minima are obtained (Figure 7). It turns out that using a small number of iterations is not enough for the system to reach a steady population. As expected, the search space is really spacious and the convergence to a different solution is highly dependent on the random initial population. The decomposition given in Figure 7a is found to be the best solution when modularity consideration has a sufficient weight to force the designs to share a component at all times.

Though the best solution agrees with the human intuition that the triangular components in the both products should be shared in some way, note that the ideal case that involves two shared components (Figure 7b) has a cost nearly %50 more than the best cost in Figure 7a. So the expected ideal configuration is essentially not feasible unless the modularity measure is far more important than the structural strength and assemblability considerations. However if some manufacturability criterion was present as well, the best solution might be disregarded due to the complex shape of the second configuration.



(a) Best solution, cost=9400 (b) Local min., cost=14,000



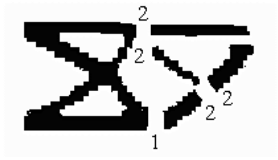
(c) Local min., cost=14,100 (d) Local min., cost= 11,400

Figure 7: The local minima for the sample problem

An important observation is that, in the modularity criteria, the term that contains the resemblance of angles cannot be made too large, i.e. the corresponding weight has an upper bound. When one tries to increase this weight to force that the shared components have similar angles, the solutions tend to avoid having part commonality. A further analysis is certainly necessary to investigate this conflict, but at this stage it will be only inferred that practically it is difficult to make the shared components have similar weld angles.

To examine the effects of the modularity terms in the objective function, the earlier version of the assembly synthesis implementation as reported in (Saitou and Yetis, 2000) is used, and the configurations that result from solely structural measures are presented in Figure 8. Figure 8a and 8b are the results for a 4-component-decomposition, and Figure 8c represents the 5-component solution for the second design problem. Note that while the optimal configuration in Figure 8a agrees with most of the local minima found in the scope of the current study, the structural measures, when applied alone, lead to different decompositions for the second problem as can be observed by comparing Figure 7 with Figure 8b and 8c.

(a) Prob.1, in 4 components (b) Prob.2, in 4 components



(c) Prob.2, in 5 components

Figure 8: Solution of the sample problem when only structural measures are used

DISCUSSION AND FUTURE WORK

It is observed that the algorithm manages to find an acceptable solution, allowing the sharing of one component by both end products and still maintaining a good structural strength and assemblability. It may be necessary, however, to carry out the synthesis with different objective function weights in a systematic way to have a complete understanding of the design. Note that this process is essentially equivalent to estimating the *Pareto set* in a multicriteria optimization problem.

The approximation used instead of a formal *graph isomorphism* check seems to be working well, obviously introducing a faster evaluation of the objective function; but for larger graphs this approximation may not be applicable. Note that there may be many subgraphs having the same number of nodes and edges but not having *isomorphism* in such cases.

It is found out that forcing the welding angles of the shared components to be similar hinders the convergence of the algorithm to one of the favorable local minima. The corresponding weight should be kept small; it seems that this criterion can even be neglected.

As a future work, one improvement may be incorporating additional objectives into the problem formulation and as a result into the fitness evaluation. Furthermore, complex modeling of joint features can be done to achieve more accurate evaluation of effect of joints on structural stiffness and strength. Ultimately, extension to 3-D structures is necessary to extend the application of the method devised in this research to real-life cases in the industry.

ACKNOWLEDGMENTS

A partial support for this work has been provided by National Science Foundation under CAREER Award (DMI-9984606) and the Horace H. Rackham School of Graduate Studies at the University of Michigan. These sources of support are gratefully acknowledged.

REFERENCES

Eng, T.-H., Ling, Z.-K., Olson, W. and McLean, C., 1999. ”Feature-based assembly modeling and sequence generation”. *Computers & Industrial Engineering*, Vol. 36, No 1, pp. 17-33.

Ishii, K., 1998. “The Life-cycle of an enterprise”, in A. Molina, J.M. Sanchez, and A. Kusiak (Eds), Handbook of Life-cycle Engineering, Kluwer Academic Publishers & Chapman and Hall, London ISBN: 0-412812509.

Kota, S., Sethuraman, K. and Miller, R., 2000. “A Metric for Evaluating Design Commonality in Product Families”. *ASME Journal of Mechanical Design,* Vol. 122, No. 4, pp. 403-410.

Lazzerini, B. and Marcelloni, F., 2000. “A genetic algorithm for generating optimal assembly plans”. *Artificial Intelligence in Engineering*, Vol. 14, No 4, pp. 319-329.

Mantripragada, R. and Whitney, D.E., 1998. “The Datum Flow Chain: A Systematic Approach to Assembly Design and Modeling”. *Research in Engineering Design*, Vol. 10, No. 3, pp. 150-165.

Nelson, S., Parkinson, M.B. and Papalambros P.Y., 1999. “Multicriteria Optimization in Product Platform Design”. *Proceedings of the 1999 ASME Design Engineering Technical Conferences*, DETC99/DAC-8676, September 12–15, Las Vegas, Nevada.

Newcomb, P.J., Bras, B.A. and Rosen, D.W., 1998. "Implications of Modularity on Product Design for the Life Cycle". *ASME Journal of Mechanical Design*, Vol. 120, No. 3, pp. 483-90.

Saitou, K. and Yetis, A., 2000. “Decomposition-Based Assembly Synthesis of Structural Products: Preliminary Results”. *Proceedings of the Third International Symposium on Tools and Methods of Competitive Engineering,* April 18-21, 2000, Delft, The Netherlands.

Senin, N., Groppetti, R, and Wallace, D.R., 2000. “Concurrent Assembly Planning with Genetic Algorithms”, *International Journal of Product Design and Process Development*, Vol. 16, No 1, pp. 65-72.

Smith, R.P., 1998. “Teaching Design for Assembly Using Product Disassembly”. *IEEE Transactions On Education*, Vol. 41, No. 1, pp. 50-53.

Stake, R.B., 1999. “A hierarchical classification of the reasons for dividing products into modules - A theoretical analysis”. Licentiate thesis, Department of Manufacturing Systems, Royal Institute of Technology, Sweden.

van Holland, W. and Bronsvoort, W.F., 2000. “Assembly features in modeling and planning”. *Robotics and Computer-Integrated Manufacturing,* Vol. 16, No. 4, pp. 277-294.

van Vliet, J.W., van Luttervelt, C.A. and Kals, H.J.J., 1999. “State-of-the-art Report On Design for Manufacturing”. *Proceedings of the 1999 ASME Design Engineering Technical Conferences*, DETC99/DFM-8970, September 12–15, Las Vegas, Nevada.

Wang, C.-H. and Bourne, D.A., 1997. “Design and Manufacturing of Sheet Metal Parts: Using Features to Aid Process Planning and Resolve Manufacturability Problems”. *Robotics and Computer-Integrated Manufacturing,* Vol. 13, No. 3, pp. 281-294.

Whitney, D.E., Mantripragada, R., Adams, J.D. and Rhee, S.J., 1999. “Designing Assemblies”. *Research in Engineering Design*, Vol. 11, No. 4, pp. 228-253.

Yao, Z., Bradley, H.D. and Maropoulos, P.G., 1998. “An Aggregate Weld Product Model for the Early Design Stages”. *Artificial Intelligence for Engineering Design, Analysis and Manufacturing*, Vol. 12, No 5, pp. 447–461.

Yu, J.S., Gonzalez-Zugasti, J.P. and Otto, K.N., 1999. “Product Architecture Definition Based Upon Customer Demands”. *ASME Journal of Mechanical Design*, Vol. 129, No. 3, pp. 329-335.