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DECOMPOSITION-BASED ASSEMBLY SYNTHESIS OF MULTIPLE STRUCTURES FOR MINIMUM PRODUCTION COST

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ABSTRACT

An extension of decomposition-based assembly synthesis for structural modularity is presented where the early identification of shareable components within multiple structures is posed as an *outcome* of the minimization of estimated production costs. The manufacturing costs of components are estimated under given production volumes considering the economies of scale. Multiple structures are simultaneously decomposed and the types of welded joints at component interfaces are selected from a given library, in order to minimize the overall production cost and the reduction of structural strength due to the introduction of joints. A multi-objective genetic algorithm is utilized to allow effective examination of trade-offs between manufacturing cost and structural strength. A new joint-oriented representation of structures combined with a "direct" crossover is introduced to enhance the efficiency of the search. A case study with two aluminum space frame automotive bodies is presented to demonstrate that not all types of component sharing are economically justifiable under a certain production scenario.

Keywords: Assembly synthesis, design for modularity, multi-objective optimization.

1. INTRODUCTION

Mechanical products are very rarely monolithic; one of the reasons is that the assembly of components allows simpler forms for the individual components, which are often more inexpensive to manufacture [1]. On the other hand, Design for Assembly (DFA) methodologies [2] often suggests the reduction of the number of components and joints to minimize the assembly cost. Further, the structural products usually favor fewer joints, since very often joints are the weakest points: for instance many fatigue failures are initiated from welded joints. The question is, therefore, "assuming a joint has to be made, what is the best method to do it?" [3]. Recognizing that the decisions on *where and how* the joints are to be made heavily impact the subsequent design processes of individual components, we have developed decomposition-based assembly synthesis [4,5], a method for the early identification of the joint locations and designs that minimally impact the overall structural strength.

Modular product design, which facilitates sharing components across multiple products, is viewed as a convenient way to offer high product variety with low production cost. The basic premise here is that the component sharing would result in less design effort and fewer production varieties with higher volumes, hence reducing overall production cost. However, component sharing has a tendency to result in overdesign of low-end products and more importantly, underdesign of high-end products in a product family [6-13]. This effect, therefore, has to be outweighed by the economical gain of component sharing to justify a decision on component sharing [6].

As an extension of our previous work on decomposition-based assembly synthesis for structural modularity [14-16], this paper presents a method for the early identification of shareable components within multiple structures, posed as an *outcome* of the minimization of estimated production costs. The manufacturing costs of components are estimated under given production volumes considering the economies of scale. Multiple structures are simultaneously decomposed and the types of welded joints at component interfaces are selected from a given library, in order to minimize the overall production cost and the reduction of structural strength due to the introduction of joints. A multi-objective genetic algorithm is utilized to allow effective examination of trade-offs between manufacturing cost and structural strength. A new joint-

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oriented representation of structures combined with a "direct" crossover is introduced to enhance the efficiency of the search. A case study with aluminum space frame automotive bodies is presented to demonstrate that not all types of component sharing are economically justifiable under a certain production scenario.

2. PREVIOUS WORK

2.1. Modular design and product platform/family

In literature, a subsystem with common components and interfaces shared across product variants is often referred to as a product platform. As there are no fundamental conceptual and methodological differences between design for modularity and design of product platforms in the context of product family design, shared parts are consistently termed as modules instead of platforms in this paper, as in our previous work [14-16].

Similar to the classification in [19], we consider two different approaches for the solution of the design for modularity problem. In *two-stage approaches,* the first stage is devoted to optimally selecting modules, followed by the second stage of deriving each product variant for optimal performance utilizing the modules. Alternatively, *single-stage approaches* simultaneously determine the module and the resulting product variants for optimal performance of individual product variants as well as a product family. Despite the higher dimensionality, the single-stage approaches are the preferred method, since two-stage approaches require *a priori* selection of modules during the stage when the impact of the module selection on product performances is not explicitly known.

One of the earlier attempts of the single-stage design for modularity is by Fujita and Yoshida [7]. They first optimize the module selection and similarity among different products using genetic algorithm, then optimize the directions of similarity on scale-based variety using branch-and-bound, and finally optimize the module attribute with sequential quadratic programming (SQP). Simpson and D'Souza's [19] presented a mixed-integer programming formulation of the single-stage design for modularity problem where binary variables represents the selection of modules within a product family and continuous variables specify parameter values associated with each module. Fellini e*t al.* [20] discussed a similar approach where the binary variables for module selection is relaxed to a continuously differentiable function that takes values in [0,1], to allow the use of gradient-based optimization algorithms. Extending the work of Simpson *et al.* [10], Messac *et al.* [21] introduced a product family penalty function to simultaneously maximize the performances of each design variant and minimize the variations in parameter values associated with chosen modules.

Focusing on the application in structural design, we have developed a method for solving single-stage approach for design for modularity based on the decomposition-based assembly synthesis [14-16]. This method has been applied to 2D continuum structures [14] and 2D [15] and 3D beam structures [16], with special emphasis on the interface (joints) between modules and other components. The present work extends the method such that the optimal modules design is achieved as an outcome of the simultaneous optimization of the performance of product variants and the manufacturing cost of a product family under particular production volumes.

2.2 Cost estimation and component sharing

Since component sharing often results in compromise in the performance of individual products, it is essential to quantify its effect on the overall production cost, in order to assess the trade-offs between cost savings and performance compromises.

Kim and Chhajed [11] developed an economic model that considers a market consisting of a high segment and a low segment. Greater commonality decreases production cost but makes the products more indistinguishable from one another, which makes the product more desirable for the low segment but less desirable for the high segment. Although the quality provided through the common design will yield the same utility, they report that there is a valuation change due to the product similarity, which affects the perceived quality of products. On the supply side, cost saving will occur if a common modular design is used for the design of multiple products. The article analyzes several sharing strategies using the cost model but does not suggest a rigorous solution for the optimization problem at hand.

Meyer *et al.* [12] proposed measurement methods of R&D performance during platform design. One measure is called *platform effectiveness*; the degree to which the products based on a product platform produce revenue for the firm relative to the cost of developing those products. Mathematically, platform effectiveness considers R&D returns as accumulated profits divided by development costs, either at the individual product level, or for groups of products within distinct platform versions. They presented a real life application, but the method is used essentially for analysis of different sharing alternatives, rather than a tool during design.

Of special interest is the work by Fisher *et al.* [13] where they presented an analytic model of component sharing and show through empirical testing that this model explains much of the variation in sharing practice for automotive braking systems. The model takes as inputs a set of cars for which brakes must be designed and a set of possible design alternatives, and determines which versions of each component should be built and which cars should use each component version to minimize cost. The cost functions model fixed and variable costs, and nonlinear production economies of scale. Similarly, Fujita and Yoshida [7] use a monotonic cost model for the assessment of benefits of commonality. The model consists of design and development cost (proportional to weight of each module), facility cost (proportional to a representative attribute) and production cost (composed of material cost and processing cost). A learning effect is incorporated by reducing the production cost in accordance with increasing number of production units due to commonality.

The specific cost evaluation approach adopted in the case study of automotive aluminum space frames in Section 4 is based on the technical cost modeling method developed at MIT Materials Systems Laboratory [22-24]. Kelkar *et al.* [22] report that the manufacture of the body-in-white is comprised of two costs: fabricating the parts and assembling the parts, with inputs of design specifications, material parameters, and production parameters. Inputs are transformed into estimates of fixed and variable costs for each manufacturing step. Variable costs include energy, materials, and direct labor; fixed costs cover capital equipment required for the manufacturing process, building expenses, maintenance etc. They present the change of the average cost of each part with respect to production volume (Figure 1), which indicates the main motivation for sharing modules in a family of products: it is possible to go down the curve by increasing the total production of the components and achieving considerable cost reduction.

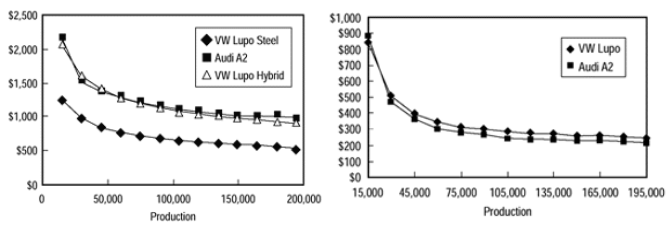


Figure 1: Fabrication and assembly costs for several automobile body structures, from [23].

3. DECOMPOSITION-BASED ASSEMBLY SYNTHESIS OF MULTIPLE STRUCTURES

3.1 Overview

The modular structural component design problem addressed in this paper is posed as an optimal selection of joint locations and joint types within two beam-based structures. Throughout the paper, *joint types* are referred to as the ways the beams are decomposed at a joint location, whereas *weld types* is the type of welding the decomposed beams are joined together, *eg.,* lap and butt welds. The approach can be summarized as follows:

- **Given:** two structures with loading conditions and their FEM results, possible joint locations, and production volumes.
- **Find:** joint locations, joint types and weld types in both structures.
- **Minimizing:** reductions in structural strength due to joints and total production cost of both structures.
- **Satisfying:** manufacturability of components.

The two given structures are assumed to bear some similarity but are distinct in the geometry and/or loading conditions. Figure 2 shows a simple example of such two variant structures. Considering a mass production environment, it is assumed that the reduction of manufacturing cost can be achieved by the improved component manufacturability as well as the increased production volume resulting from component sharing within variants.

For the given variant structures the designer defines the possible locations where a joint can be placed. While the following examples simply assume joints can be placed at any intersections of beams in the structures, the designer may choose to allow joints to be placed only at some intersections or in the middle of some beams. For each possible joint location, the designer also must provide a *joint library*, feasible types of joints at the location, among which the optimal selection can be made. Figure 3 shows an example decomposition of the structures in Figure 2, where the selected joint types are shown as numbers with the arrows indicating which beam is welded onto another. The two triangular components annotated with "s" are sharable components between the structures. Note that the sharable components identified automatically during the optimization, as a outcome of minimizing the overall manufacturing cost.

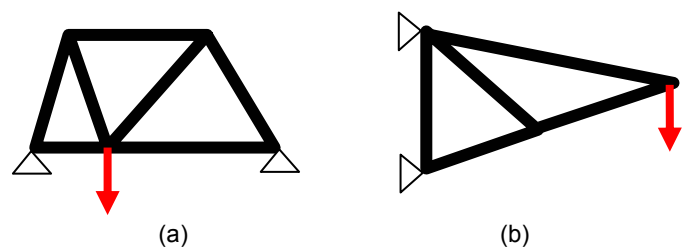


Figure 2. Example of two beam-based product variants.

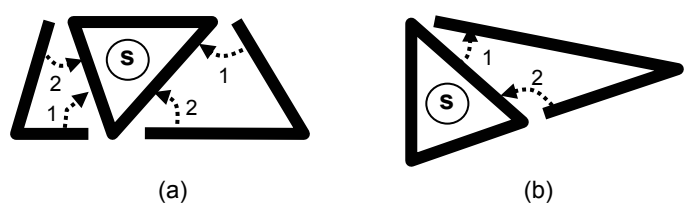


Figure 3. Example decomposition of the product variants in Figure 2. The selected weld types are shown as numbers with the arrows indicating which beam is welded onto another. The identified sharable components are annotated with "s".

While overall steps of assembly synthesis described above is virtually identical to those found in [14-16], the distinct features of the present approach are 1) a new joint-oriented representation of structures, rather than topology graphs, which ensures the topological feasibility of decomposition without additional constraints, and 2) the identification of sharable components as an *outcome* of minimizing the overall production cost, rather than simply maximizing the number of shared components. To quantify the cost reduction of component sharing (assumed to be primarily due to the economy of scale), production volumes of both variants are provided as an input to the cost estimation function; details are described in the following sections.

3.2 Definition of design variables

Let $L_1 = \{1,2,\ldots N_1\}$ and $L_2 = \{1,2,\ldots N_2\}$ be the sets of possible joint locations in the given two structures, structure 1 and 2, defined by the user. The design variables $\boldsymbol{x}_1$ and $\boldsymbol{x}_2$ are the vectors of the *joint types* in structure 1 and 2, respectively:

$$\boldsymbol{x}_1 = (x_{11}, x_{12}, \ldots, x_{1N_1});\ x_{1i} \in J_{1i},\ i \in L_1 \quad (1)$$

$$\boldsymbol{x}_2 = (x_{21}, x_{22}, \ldots, x_{2N_2});\ x_{2i} \in J_{2i},\ i \in L_2 \quad (2)$$

where J_{1i} and J_{2i} are the sets of feasible joint types, including a type specifying no joint, defined at each possible joint location in the structures. These sets are provided by the designer based on the material, manufacturing process and geometry of the structure. In the present study, joint types are defined as follows:

$$J_{ki} = \begin{cases} \{0,1,2\} & \text{if location } i \text{ is at a 2-beam intersection} \\ \{3,\ldots,14\} & \text{if location } i \text{ is at a 3-beam intersection} \end{cases} \quad (3)$$

where $k \in \{1, 2\}$ and joint types 0,…, 14 are illustrated in Figure 4, where ioint type 0 corresponds to no joint and the arrows indicate which the beam is welded onto another. It is assumed a beam cannot be weld onto more than one beam. The beams that the arrows are incident from (the beams welding onto other beams) are referred to as the *welding beams*. Note that three-beam intersection[1] must be always decomposed since branching beams cannot be manufactured with extrusion.

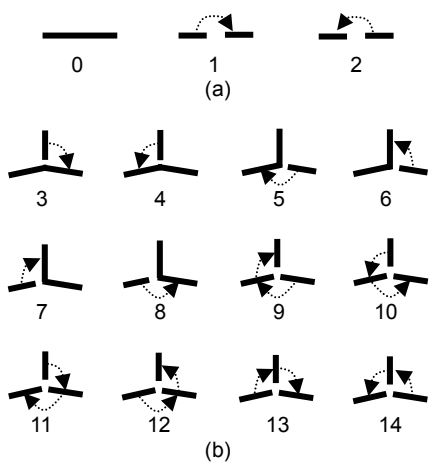
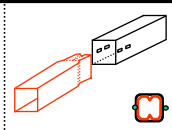
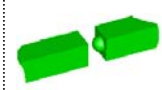
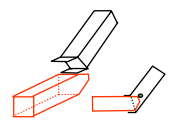
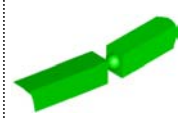
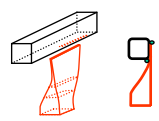
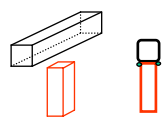
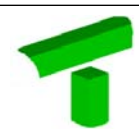


Figure 4. Joint types of (a) two-beam intersection (types 0-2) and (b) three-beam intersection (types 3-14). The arrows indicate which beam is welded onto another. Note that three-beam intersection must be always decomposed since branching beams cannot be manufactured with extrusion.

Considering the application to automotive aluminum space frame (ASF) bodies, it is assumed that the structures are made of extruded aluminum beams joined via MIG or laser welding. Accordingly, each arrow in Figure 4 indicates a weld of a type among the four weld types in Table 1 [25], where the gray (red in color printing) beam indicates the welding beam (the beam weld onto another beam). Note that only one weld type is possible if the joined beams are uniaxial (type A) and oblique (type B), whereas two weld types (types C and D) are possible between the beams perpendicular to each other.

In order to uniquely define the joint at location i, one must not only specify a joint type, but also a weld type. While design variables $\boldsymbol{x}_1$ and $\boldsymbol{x}_2$ specify a joint type at each possible joint location in structures 1 and 2, a weld type is selected such that the weld will be subject to minimum force, as described in the following section.

Table 1. Weld types of extruded aluminum beams for space frame bodies [25]. Gray (red in color printing) beams indicate the welding beams.

type	weld type	description	simplified representation
A		uniaxial	
B		oblique	
C		perpendicular lap	
D		perpendicular butt	

3.3 Definition of constraints

While joint types in Figure 4 guarantee there will be no branching beams in a structure, it may still be possible for a component to have complex bends requiring sophisticated bending processes. Assuming all beams are bent without a costly CNC bender, a manufacturability constraint is imposed to ensure all components in a structure are 'flat" without out-of plane bends:

$$\text{FLAT}(\boldsymbol{x}_k) = \text{TRUE} \quad (4)$$

where $k \in \{1, 2\}$. Figure 5 (a) shows an example of such an infeasible component, which can be made feasible, for example, by the introduction of an additional joint as shown in Figure 5 (b). The cost of in-plane bends in a structure is accounted for as a part of manufacturing cost, as discussed in the following section.

[1] No branch involving more than 4 beams are assumed in the structures.

(a) (b)

Figure 5. (a) infeasible component with an out-of-plane bend and (b) feasible components without out-of-plane bends.

3.4 Definition of objective functions

3.4.1 Structural strength

Since weld joints are the locations where fatigue failures are often initiated, their excessive use will reduce the overall structural strength. It is assumed that the tensile and shear forces have the same effect on the strength of the weld, since the experimental results in the literature [26-32] do not suggest an obvious preference between shear and tensile forces. As a "first order" estimate suitable to early conceptual design stage, therefore, the reduction of structural strength is simply calculated as the total force exerted to the welds in a structure.

$$f_s(\boldsymbol{x}_k) = \sum_{i \in L_k} F(x_{ki}) \tag{5}$$

where $k \in \{1, 2\}$. $F(x_{ki})$ is the force on the weld(s) at location i in structure k, which depends on the joint type x_{ki}. Obvisouly, $F(x_{ki}) = 0$ if $x_{ki} = 0$ (no joint). Noting that joint types 1-8 have only one weld whereas joint types 9-14 have two welds, $F(x_{ki})$ can be obtained by selecting the weld types(s) in Figure 5 that gives the minimum force at the location:

$$F(x_{ki}) = \begin{cases} \min\limits_{w \in W(x_{ki})} F_w & \text{if } x_{ki} \in \{1, \ldots 8\} \\ \min\limits_{(w,v) \in WV(x_{ki})} (F_w + F_v) & \text{if } x_{ki} \in \{9, \ldots, 14\} \end{cases} \tag{6}$$

where

- $W(x_{ki}) \subseteq \{A, B, C, D\}$: a set of feasible weld types of joint type $x_{ki} \in \{1,.., 8\}$ at location i of structure k.
- $WV(x_{ki}) \subseteq \{A, B, C, D\}^2$: a set of pairs of feasible weld types of joint type $x_{ki} \in \{9,..,14\}$ at location i of structure k.
- F_w: force of weld type w.

Assuming the compressive forces on the mating surface will be carried by the beams themselves and not by the welds, the force exerted on the weld of each type in Figure 5 is given as:

$$F_w = \begin{cases} |F^a| & \text{if } w \in \{A, B\} \\ \sqrt{\{\max(0, F^t)\}^2 + \{F^a\}^2} & \text{if } w = C \\ \sqrt{\{\max(0, F^a)\}^2 + \{F^t\}^2} & \text{if } w = D \end{cases} \tag{7}$$

where F^a and F^t are the axial and transversal forces on the welding beam. In Equation (7), F^t for weld type C and F^a for weld type D are measured in the direction of the tension in the mating surface (*i.e.,* compression is negative) in Table 1.

3.4.2 Production cost

The cost of a structure consists of component cost and assembly cost. Since the introduction of joints does not change the total material use in a structure and extrusion is a low cost process, it is assumed that component cost only depends on the cost of bending. Similarly, assembly cost is assumed to be only dependent on the cost of welding. Therefore, the total cost of producing one unit of structure 1 and one unit of structure 2 is given as:

$$f_c(\boldsymbol{x}_1, \boldsymbol{x}_2) = f_c^w(\boldsymbol{x}_1, \boldsymbol{x}_2) + f_c^b(\boldsymbol{x}_1, \boldsymbol{x}_2) \tag{8}$$

where $f_c^w(\boldsymbol{x}_1, \boldsymbol{x}_2)$ and $f_c^b(\boldsymbol{x}_1, \boldsymbol{x}_2)$ are the total cost of welding and bending to produce one of each structure, respectively. The total welding cost is broken down to:

$$\begin{aligned} f_c^w(\boldsymbol{x}_1, \boldsymbol{x}_2) = {} & c^w((n_1^w - n_{12}^w)q_1) \times (n_1^w - n_{12}^w) \\ & + c^w((n_2^w - n_{12}^w)q_2) \times (n_2^w - n_{12}^w) \\ & + c^w(n_{12}^w(q_1 + q_2)) \times 2n_{12}^w \end{aligned} \tag{9}$$

where

- $c^w(q)$: cost of a welding operation for production volume q.
- n_1^w: number of welds in structure 1 (function of $\boldsymbol{x}_1$).
- n_2^w: number of welds in structure 2 (function of $\boldsymbol{x}_2$).
- n_{12}^w: number of welds in the modules shared in structures 1 and 2 (function of $\boldsymbol{x}_1$ and $\boldsymbol{x}_2$).
- q_1: production volume of structure 1 (user input).
- q_2: production volume of structure 2 (user input).

The first and second terms of Equation (9) represent the costs of welds appearing only in structure 1 and structure 2, respectively. The third term is the cost of welds in the modules shared in both structures. The breakdown of the total bending cost is given similarly (by replacing superscript w with b).

The unit cost of welding and bending operations $c^w(q)$ and $c^b(q)$, as a function of production volume q, are obtained by [23] and [24], respectively, Table 2 lists some of the actual values used in the calculation of Equation (8), which exhibits a basic trend of economies of scale: exponential cost decrease similar to Figure 1. Due to this trend, it is possible to reduce the cost of shared modules due to the increased production volume. While the weld cost is higher than bend cost at all production volumes, it decreases more rapidly as the production volume increases, reaching to nearly the same amount as the bend cost at higher production volumes. The values (and the

interpolations of them) in Table 2 are used for all weld types in Table 1 and any bends except for the ones with the total bend angle exceeds 180°. The cost is doubled for such bends considering the process difficulty.

Table 2. Unit costs of bending and welding operation as a function of production volume [23, 24].

q [units]	$c^w(q)$ [$]	$c^b(q)$ [$]
30	4.4	2.9
60	2.8	2.4
90	2.3	2.1
120	2.2	2.0
180	2.1	1.9

To obtain the numbers of shared welds and bends, n_{12}^w and n_{12}^b, the components shared in structures 1 and 2 need to be identified first. This is done by checking the similarity of each pair of components (c_1, c_2) in structures 1 and 2 as specified by $\boldsymbol{x}_1$ and $\boldsymbol{x}_2$, which are determined progressively by applying the following criteria in the sequence:

1. Area of the bounding box (close within a given tolerance)
2. Total bend angle (close within a given tolerance)
3. Number of welds (identical).
4. Topology (identical).

The component pairs (c_1, c_2) that passed all four criteria are considered as sharable and included in the calculation of n_{12}^w and n_{12}^b. The tolerances in criteria 1 and 2 control the degree to which two components are considered to be similar and hence sharable. These tolerances are adjusted to appropriate values in order to allow effective exploration of potential sharing options during the early design stages.

3.5 Formulation of optimization problem

The design variables, the constraints, and the objective functions defined in the previous sections provide the following multi-objective optimization problem:

$$\begin{aligned} &\text{minimize:} \quad \{f_s(\boldsymbol{x}_1) + f_s(\boldsymbol{x}_2),\ f_c(\boldsymbol{x}_1, \boldsymbol{x}_2)\} \\ &\text{subject to:} \\ &\qquad \boldsymbol{x}_1 \in J_{11} \times J_{12} \times \cdots \times J_{1N_1} \\ &\qquad \boldsymbol{x}_2 \in J_{21} \times J_{22} \times \cdots \times J_{2N_2} \\ &\qquad \mathrm{FLAT}(\boldsymbol{x}_1) = \mathrm{TRUE} \\ &\qquad \mathrm{FLAT}(\boldsymbol{x}_2) = \mathrm{TRUE} \end{aligned} \tag{10}$$

For given production volumes of structures 1 and 2, this problem is solved using a multi-objective genetic algorithm (GA) as described in the next section.

3.6 Optimization algorithm

Due to its combinatorial nature, solving the above problem requires a discrete optimization algorithm. As such, a multi-objective genetic algorithm (GA) was chosen, due to the robustness to discrete problems and efficiency in handling multi-objective problems without predefined weights or bounds on objective functions. The implementation used in the following case study is based on Non-Dominated Sorting Genetic Algorithm (NSGA-II) [17,18], which dynamically determines an aggregate of multiple objective values of a solution based on its relative quality in the current population, as the number of other solutions dominating it in the current population.

A new joint-oriented representation of structures described in Section 3.2 allows a chromosome (an internal representation of design variables in GA) to be simply a linear concatenation of $\boldsymbol{x}_1$ and $\boldsymbol{x}_2$:

$$\boldsymbol{c} = (\boldsymbol{x}_1, \boldsymbol{x}_2) \tag{11}$$

To enhance the search efficiency of GA, a "direct" crossover [16, 33-38] scheme is adopted, which directly acts on phenotype (structures in 3D space in our case) rather than on genotype (a linear list of numbers in Equation (11) in our case) as the conventional crossovers. As in [16], this is achieved by:

1. Select a random point within the bounding box of two structures and select a random orientation.
2. Construct the plane that passes the point with the orientation.
3. Slice two parent structures with the plane and then swap the resulting substructures to produce two offspring structures.

The crossover that directly operates on structures has an apparent advantage of preserving the local building blocks in the structures, which seems to significantly contribute to the improved search efficiency. While some bias could be introduced in selecting a point and an orientation in Step 1, uniform probabilities are used in the following case study.

To further improve the search efficiency, a repair operator is applied to the offspring structures if they become infeasible to the manufacturability constraint in Equation (4). This is done, whenever possible, by enforcing the decomposition of the components with out-of-plane bends into the beams without them. For example, an infeasible component in Figure 5 (a) can be decomposed to two feasible components in Figure 5 (b).

A software implementation of the optimization problem is done using the C++ programming language using the LEDA library from the Max-Planck Institute of Computer Science. ABAQUS software by Hibbitt, Karlsson & Sorensen, Inc is used for the finite element analyses. Multi-objective genetic algorithm code and visualization software for space frame structures are written by Karim Hamza and Byungwoo Lee, respectively, at the Discrete Design Optimization Laboratory at the University of Michigan.

4. CASE STUDY

4.1 Structural models

This section describes a case study of example 3D aluminum space frame models under global-bending loading condition, as shown in Figure 8. It is assumed that these frame designs are still preliminary with no consideration of component sharing (hence vastly different in geometry). The aim is to identify the options for potential component sharing that would results in the reduction of overall manufacturing cost, prior to the detailed design of each frame. Structure 1 (compact vehicle in Figure 8 (a)) is approximately 3.80 [m] in length (x direction), 1.70 [m] in width (y direction), and 1.55 [m] in height (z direction). Structure 2 (mid-size vehicle in Figure 8 (b)) is approximately 5.00 [m] in length, 1.90 [m] in width, and 1.45 [m] in height. Beams are modeled as hollow tubes with rectangular cross sections of 50×50 [mm] or 75×75 [mm], with the wall thickness of 2 [mm]. The material is taken as a typical aluminum alloy with the modulus of elasticity of 74 [GPa]. Assuming left-right symmetry of component geometries, only a half body is modeled as shown in Figure 8.

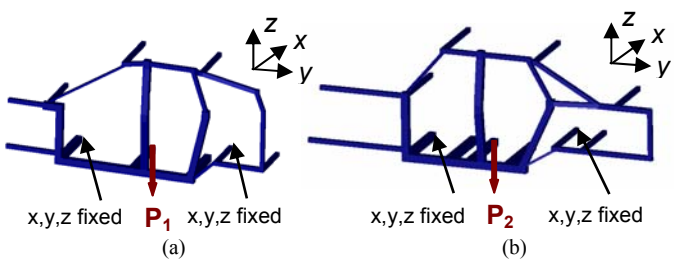


Figure 6. Example aluminum space frame structures under global bending condition. (a) structure 1: compact vehicle subject to downward force P_1 = 895 [kg] and (b) structure 2: mid-size vehicle with P_2 = 1770 [kg].

4.2 Production volumes

To examine the impact of production volumes on the optimal decompositions, the following three scenarios of the production volumes are considered:

- **Scenario 1:** $(v_1, v_2) = (30{,}000, 30{,}000)$.
- **Scenario 2:** $(v_1, v_2) = (90{,}000, 30{,}000)$.
- **Scenario 3:** $(v_1, v_2) = (90{,}000, 90{,}000)$.

where v_1 and v_2 are the annual production volumes of structure 1 (compact vehicle) and structure 2 (mid-size vehicle), respectively.

4.3 Optimization results

Figure 7 shows the Pareto solutions of the three scenarios obtained by the multi-objective GA, where the horizontal and vertical axes are the production cost of two structures ($f_c(\boldsymbol{x}_1, \boldsymbol{x}_2)$) and total forces on welds of two structures ($f_s(\boldsymbol{x}_1) + f_s(\boldsymbol{x}_2)$) as given in Equation 10. Table 3 lists typical values of run-time parameters of GA used to obtain the result.

The relative locations of the three Pareto solutions in Figure 7 provide the following observations:

- Production cost increases (*i.e.*, Pareto solutions shift to the left) as the production volume increases from Scenario 1 to Scenario 3. This is due to the reduction in costs of welding and bending at high production volume.
- Force on welds increases (*i.e.*, Pareto solutions shift up) as the production volume increases from Scenario 1 to Scenario 3. This is due to the increased preference of welds to bends for achieving low production cost at high production volume.

In Scenario 1, welds are not desired at all as they are expensive and also increase the total force on welds, preferring complex components with multiple bends. This scenario also prefers modules since the effect of increased production volume on cost reduction is larger at smaller production volumes. In fact less modules are observed in Scenario 3 due to their minute effect on the cost reduction.

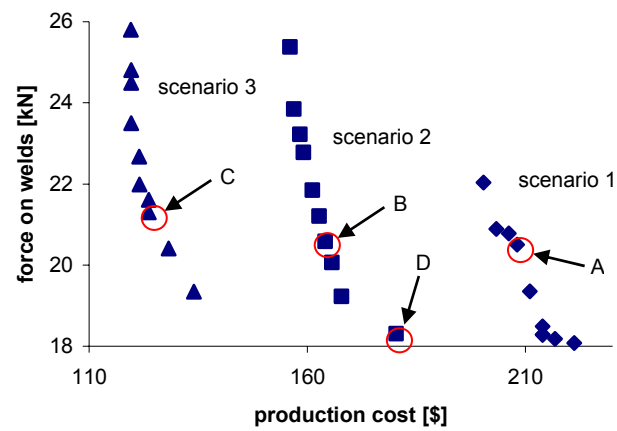


Figure 7: Pareto optimal solutions for scenarios 1: (v_1, v_2) = (30,000, 30,000), scenario 2: (v_1, v_2) = (90,000, 30,000) and 3: (v_1, v_2) = (90,000, 90,000).

Table 3. Typical run-time GA parameters used in the case study.

Population size	100
Number of generations	1000
Crossover probability	90%
Mutation probability	1%

The decomposed structures at points A, B, C, D in Figure 7 are shown in Figures 8-11, respectively, where weld types are represented graphically as shown in the third column of Table 1. Figure 8 shows the decomposed structures at point A (Scenario 1). The structures exhibit relatively small number of welds (*i.e.*, complex components with multiple bends) and two shared modules s_1 and s_2, both of which contribute to cost reduction under the production volumes of Scenario 1.

Examinations of other points revealed that the same two modules appear at every point of the Pareto solutions, with the rest of the structures decomposed differently. It should be noted that some modules do not have exactly identical geometry. This is because two components are considered sharable if they are geometrically similar within predefined tolerances as stated in Section 3.4.2, to allow effective exploration of potential sharing options before the detailed design of each frame.

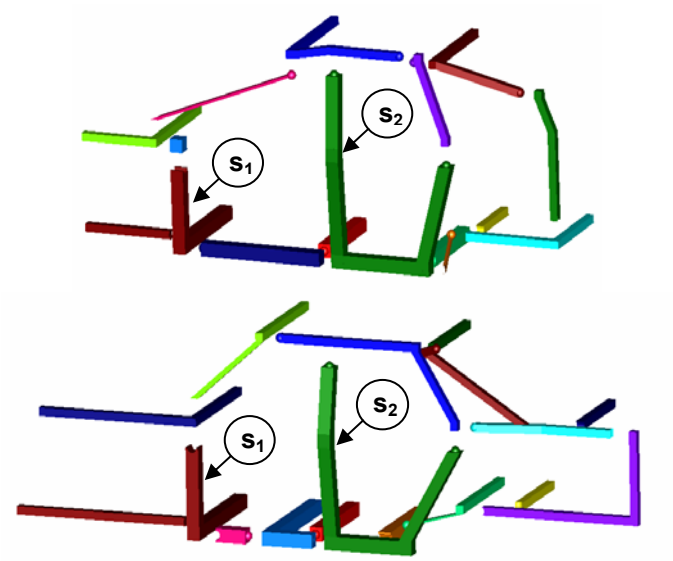


Figure 8: Decomposed structures at point A in Figure 7.

Figure 9 shows the results in point B (Scenario 2) that also contain two modules. While module s_1 is identical to the one in Figure 8, the large three-bend module in Figure 8 is replaced by a small two-bend module (appearing in a rather creative fashion from the conventional body design viewpoint), due to the increased production volume of structure 1. Since there is very little cost reduction of having modules at high production volumes no module appeared in the results of point C (Scenario 3) as seen in Figure 11. This is also true for the other points for Scenario 3, except for possibly random emergence of a few modules.

Figure 11 shows the decomposed structure at point D (Scenario 2) with the minimum force on weld but maximum production cost. Since two structures are produced at different volumes in Scenario 2, there is a cost incentive to make a low volume model (structure 2) similar to a high-volume model (structure 1). This can be observed by comparing the decompositions at point D (Figure 11) and point B (Figure 9). As the cost decreases from points B to D, the decomposition of structure 1 is kept constant, whereas the decomposition of structure 2 become more similar to structure 1 as indicated by the increased number of modules (from 1 to 2).

In all results, there is virtually no uniaxial joint since the decomposition of a straight member with no bends simply increases the force on welds with no cost reduction. Relatively small number of identified modules is due to the tolerances (80%) in the similarity check described in Section 3.4.2, which might be tight for the two structures (modeled after existing vehicles) with not very similar dimensions.

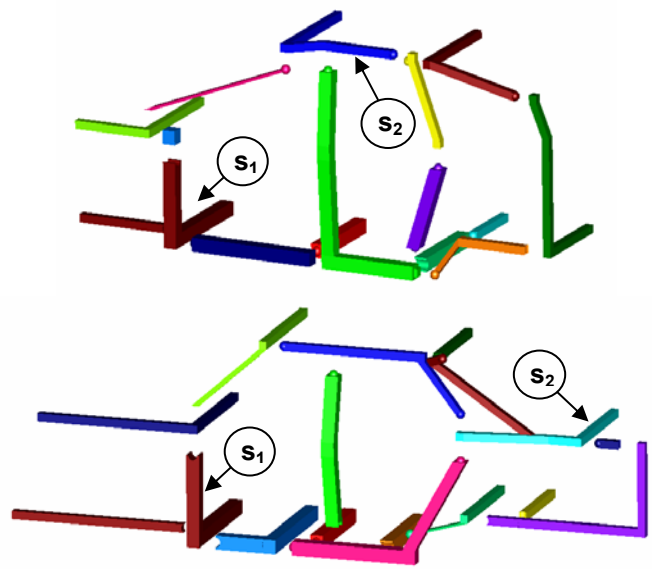


Figure 9: Decomposed structures at point B in Figure 7.

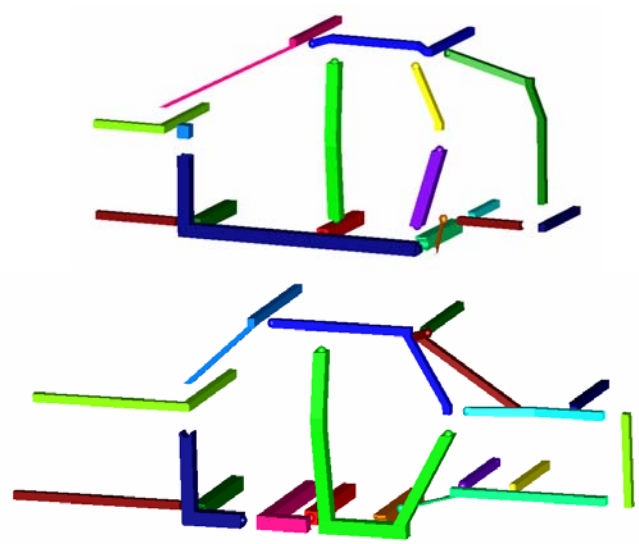


Figure 10: Decomposed structures at point C in Figure 7.

5. DISCUSSION AND FUTURE WORK

This paper discussed an optimization-based method for simultaneous decomposition of multiple structures considering structural strength and production cost, where the identification of sharable modules is achieved as an outcome of minimizing manufacturing costs in a certain production scenario. A case study with automotive aluminum space frames demonstrated that the method can successfully quantify the effect of module sharing on structural strength and production cost, by means of Pareto optimal solutions. Each Pareto optimal solution can be

evaluated by a human decision maker before further design details are considered. Depending on the priorities with regard to strength and cost, solutions with balanced trade-offs (*eg*., points A,B,C in Figure 7) or extreme points (*eg*., point D in Figure 7) can be selected.

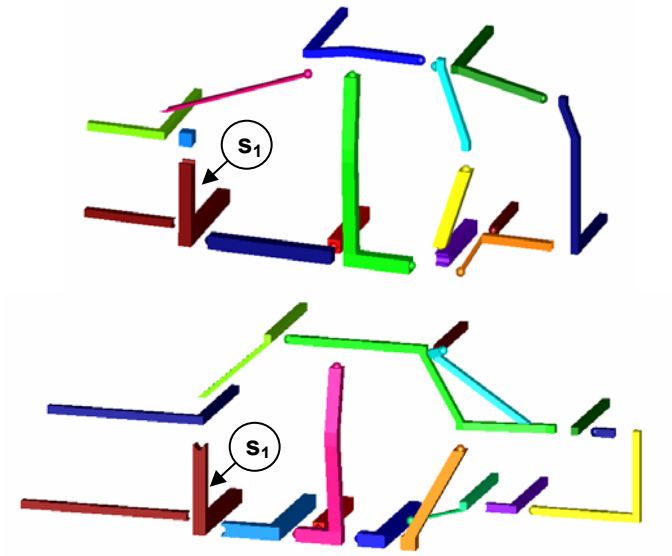


Figure 11: Decomposed structures at point D in Figure 7.

Not surprisingly, the effect of module sharing is negligible at larger production volumes (Scenario 3), as the economies of scale already provide a low cost for each component. On the other hand, modularity is an effective strategy at lower production volumes (Scenarios 1 and 2) for this specific application of space frame models. It should be noted, however, that the Pareto optimal solutions are quite sensitive to the unit cost of welds and bends and how they vary as a function of production quantity. While this sensitivity is quite natural (as it is the cost that drives the decomposition), a care should be taken on the accuracy of the cost model (Table 2 in this paper) to apply the present methods to products made with other manufacturing processes.

While promising, there are number of refinements needed for the present approach to be more practical. These include the refinement of structural strength evaluation such as the inclusion of the moments on welds in Equation (5), more strict similarity check such as matching the force and moment at joints, and the identification of modules that are insensitive to the future changes in design details, such as dimensions. These extensions are to be reported at future opportunities.

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