AN OPTIMIZATION-BASED APPROACH FOR SUPPORTING EARLY PRODUCT ARCHITECTURE DECISIONS

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Abstract

An important aspect in designing the product architecture of turbo fan engine structural components is the load path and flow path of the components. We present an approach for deciding the preliminary load carrying configuration or LCC (arrangement of structural elements to carry loads) for a generic, static engine structure during early design phases. The LCC, which is a part of the load path aspect, withstands multiple load cases during engine operation. Each such load case for the LCC can be represented as an interface stiffness optimization problem. Our approach for deciding the preliminary LCC involves individual consideration of a number of problems (load cases), down-selecting a small number of interesting problems, and running a coordinated optimization for the down-selected problems using the non-hierarchical coordination. The optimization yields a compromise solution that can be considered as a starting point for detail design of the integrated product. This approach may allow better design resources allocation, as the obtained solution satisfies a number of load cases on the structure.

Keywords: Early design phases, Product architecture, Multi- / Cross- / Trans-disciplinary processes

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1 INTRODUCTION

Product architecture, defined as the allocation of functional elements to physical elements (Ulrich, 1995), is important information for any company as it influences the design, manufacture and service of their products. Two types of architecture exist, modular and integral. For modular architecture products, individual functions required of the structure is carried out by one or several dedicated components while for integral architecture products one single component (or a group of components) satisfy several functions required of the component. An aircraft turbo fan engine consists of both modular and integral architecture components. Static structures in the engine that connect different engine modules (such as compressors and turbines) are typical examples of integral architecture products in an engine. One single component, in many cases one single cast or fabricated structure, satisfies several functions. Levandowski et al. (2014) refer to such products as integrated products.

In general, the main function of a static structure is transfer of core flow (a gas flow path) between two engine modules and carry loads (a mechanical load path) such that the engine's structural integrity is maintained. In principle, the load path and flow path determine how the structure's design should be carried out to fulfill its function. In other words, the load path and flow path determine the architecture of a static structure. Requirements on the flow path and load path need to be balanced for a well performing structure, in aerodynamic (minimum loss to the flow) and structural terms (maintaining integrity). In practice, the designs are also constrained by manufacturability and maintainability considerations, but these are not included explicitly in this study.

The working of different modules (compressors or turbines) and the requirements on them influence load path and flow paths for a structure since the interface positions are influenced by the individual module designs. For a component developer, until the interface positions are available, designs cannot be carried out in full. However, the interface information is not readily available at the start of a development program (typically a delay of 4 to 6 months can occur) as the engine OEMs too would not have finalized their module designs. This information delay causes a delay in the detail design for the static structural components which can result in misjudgment about technologies that need to be utilized in the manufacture of the component, making the design uncompetitive. Component developers overcome this problem by considering a number of architectures for early evaluations based on previous experience and preliminary aero-thermodynamic calculations. This paper addresses the problem of early selection and optimization of architecture options for integrated aerospace components such that good candidate architecture is chosen for detail design. Specifically, we demonstrate the applicability of non-hierarchical analytical target cascading, a coordination method for multidisciplinary design optimization, to the architecture selection problem. We detail an approach in which a compromise design for the load path aspect of the integrated product architecture can be found. The compromise solution sufficiently withstands a number of different loading scenarios on the structure and therefore, is a good candidate for detail design.

2 BACKGROUND AND OBJECTIVE

A jet engine consists of a number of static structures that together with the rotors build up the overall structure of the engine. Here, we consider a turbine rear structure (TRS) as a representative static structural component. The TRS is located just after the low-pressure turbine (LPT) as shown in Figure 1. The structure has several functions such as redirecting the air-flow from the turbine and transmitting the mechanical bearing loads towards the engine outer-case.

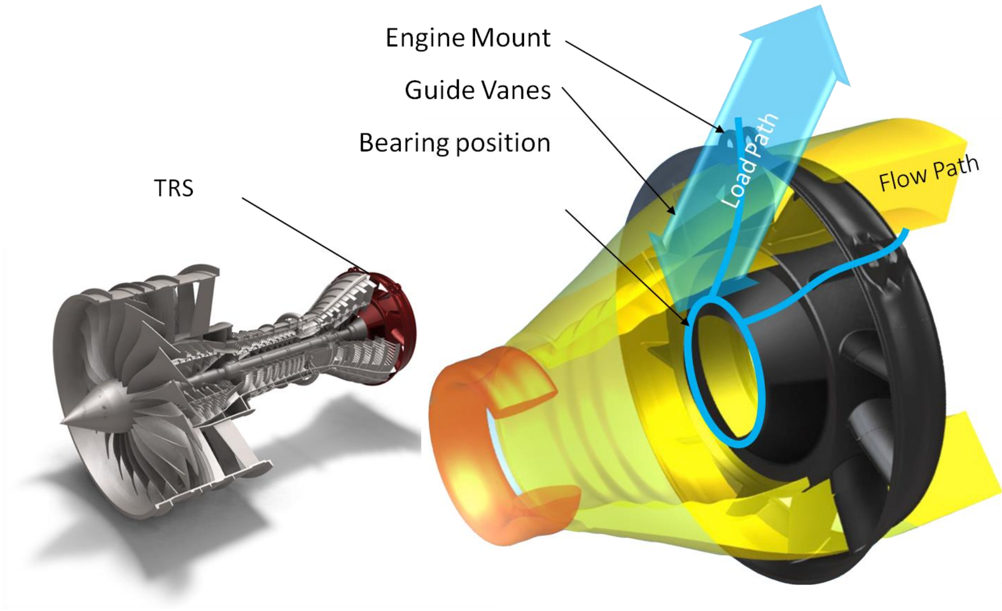

Figure 1. The Turbine Rear Structure (TRS), the flow path (gas) and load path (mechanical)

With respect to the load transmitting function, a typical, simplified Load Carrying Configuration (LCC) of the structure is shown in Figure 2. The LCC is simply the arrangement of structural elements such that an applied load is transmitted from one point to a desired another point. The construction consists of an annulus the walls of which are connected by a number of vanes. The outer wall and inner wall of the structure that creates the flow annulus along with the vanes that connect the annulus is marked in Figure 2. The locations at which the structure is connected with other components in the engine (interfaces) determine the layout of the LCC. During early stages of engine design, it is possible for a static structure designer to get an initial estimate of interface locations from preliminary aero-thermodynamic calculations (using mean-line turbine design codes) and previous experience, and then choose a geometrical configuration for carrying loads. Past experience plays a role since basic architecture of such products has remained the same for many years, similar to the case reported by (Wyatt, 2009) for other integrated complex products such as diesel engines.

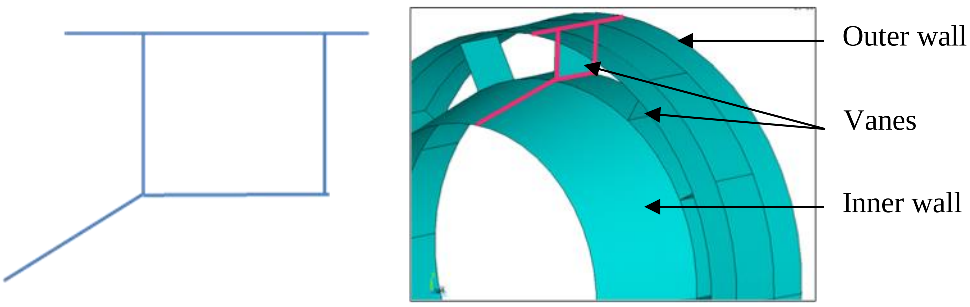

Figure 2. Typical load carrying configuration, highlighted on a static structure

The scope of this paper is the architectural design of jet engine structures which are of integrated product architecture. The objective of this paper is to present an approach that could be adopted for deciding the preliminary load carrying configuration (LCC) for a generic, static aero engine structure. Therefore, this paper addresses only one architectural aspect of static aero engine structures, the mechanical load path. The gas flow path aspect of the architecture is not considered in this preliminary study. A number of LCCs might be possible for the structure resulting from the engine level architectural choices. In this paper, only one option is selected for the LCC. From a number of possible loading scenarios on the LCC, two interesting loading scenarios are selected and are coordinated as an optimization problem using the non hierarchical analytical target cascading (NHATC) (Tosserams et al., 2010) method to obtain one single, compromise solution. The compromise solution is to have the maximum stiffness by means of the geometry of the structure alone. Following sections detail the generation of a single compromise load carrying configuration design that satisfies a number of loading scenarios.

3 LOAD CARRYING CONFIGURATION DESIGN APPROACH

3.1 Loading scenarios and optimization problem formulations

The idealized cross section of the TRS is represented by a configuration of geometrical positions, called "points", and their coordinates available for design, serve as design variables. The combined changes of interfaces and where and how the component is integrated into the engine are sufficient to illustrate architectural options considered on the engine system level. Figure 3 shows the sectional view for the load carrying configuration. Points 1, 2 and 3 are the interface points, where other engine components are attached to the structure. Typically, point 1 corresponds to forward flange interface; point 2 corresponds to aft flange interface, and point 3, the interface to the respective bearing for any of the engine shafts. Loads are primarily transmitted to and from the structure through these interfaces. The vanes (marked in Figure 2) take part in the load transfer from point 3 to 1 or 2 as well as from 1 to 2 or from 2 to 1. For this configuration, the stiffness of the structure will thus be dependent on the number and position of the vanes in the structure. Therefore, if this LCC needs to be optimized for maximum stiffness, the design variables will be the number and position of the vanes. Referring to Figure 3, by changing the axial and radial position of points 4, 5, 6 and 7, the sectional shape of the structure can be changed. Variables a, b, c, d, e, f, g and h represent the allowable axial and radial positions for the structure at points 4, 5, 6 and 7. These variables are also marked in Figure 3. In addition to the position of vanes another variable that affects the load transfer is the number of vanes, represented by i. The number of vanes, besides affecting the load transfer effectiveness, affects the weight of the structure. The number of vanes needs to be traded for high stiffness and low weight. (Stiffness and weight are not the only considerations here. For the engine core flow to pass through the annulus with as minimum loss as possible a certain minimum number of vanes is required that sets constraints on the number, shape and position of vanes. This detail of the problem is related to the flow-path aspect of the integrated architecture structure and is not considered in this paper).

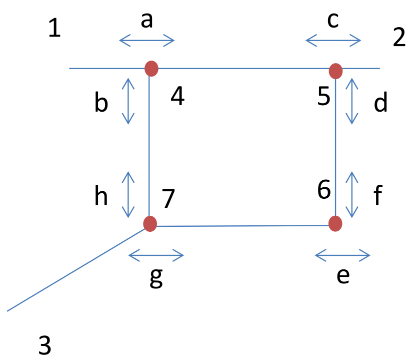

Figure 3. Design variables for the load carrying configuration

The different loading scenarios on the structure are shown in Figure 4. Problems 1 and 2 have the same boundary conditions. A unit load is applied at point 3 (the bearing interface) while point 1 (the fore flange interface) is fixed. In problem 1, a unit force load (10000 N) is applied at point 3 while for problem 2, a unit moment (1000 Nm) is applied at point 3. Problems 3 and 4 are similar to 1 and 2 with the difference that a fixed boundary condition is moved from point 1 to point 2. Similar to problems 1 to 4, problems 6 to 9 also have loads applied at one of the interfaces while the other interface is fixed. Problem 5 is simply a weight minimization problem. Problems 1 through 9 represent typical arrangements where both the component architecture and its interplay with the engine system architecture result in non-convex optimization problems with both continuous and integer variables.

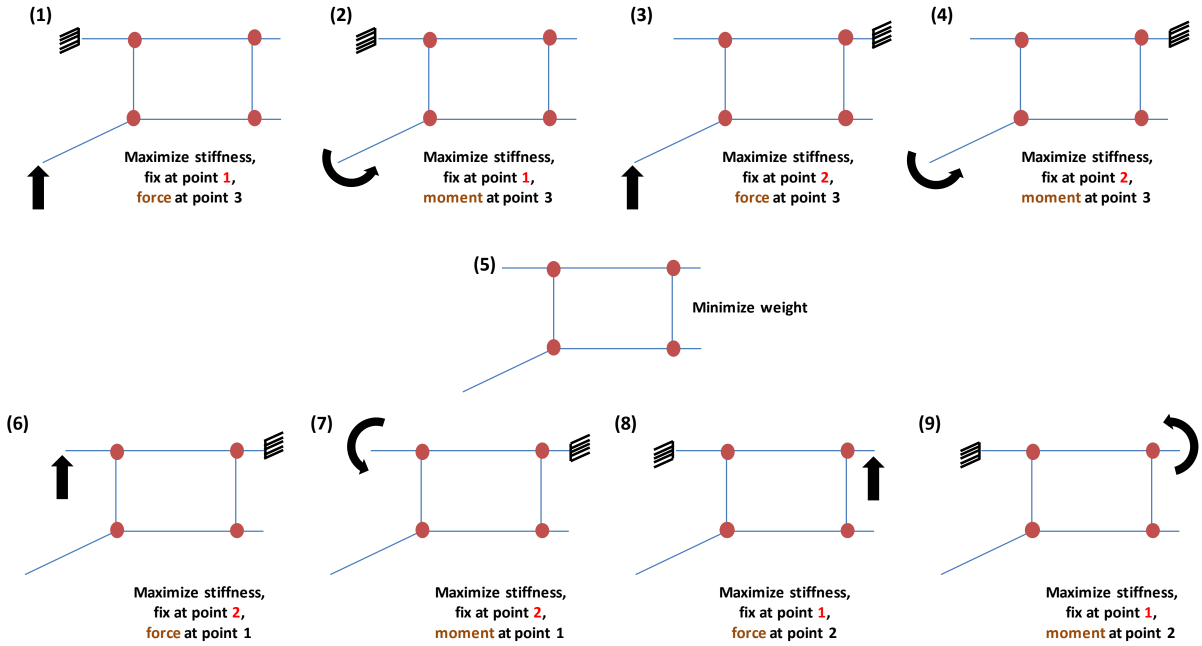

Figure 4. The different loading scenarios on the LCC

An individual problem, for maximizing interface stiffness can be written as:

$$\min_{\mathbf{G}_\mathrm{p}} \quad -K_p = -\frac{F}{\delta(\mathbf{G}_\mathrm{p})} \tag{1}$$

Subject to $\mathbf{G}_\mathrm{lower} \leq \mathbf{G}_\mathrm{p} \leq \mathbf{G}_\mathrm{upper}$,
where K_p is the stiffness for the interface under load application for problem p, F is the force (or moment) applied at the interface, and δ is the displacement (or rotation) in the direction of force (or moment) application at the interface. $\mathbf{G}_\mathrm{p}$ is the vector of design variables for problem p, and $\mathbf{G}_\mathrm{lower}$ and $\mathbf{G}_\mathrm{upper}$ are the vectors of upper and lower bounds on the design variables. δ, the displacement (or rotation) in the direction of force (or moment) F, varies depending on the design variables. The vector of design variables is $\mathbf{G}_\mathrm{p} = [\mathrm{a,b,c,d,e,f,g,h,i}]_\mathrm{p}$. $\mathbf{G}_\mathrm{p}$ has 8 real valued variables representing the positions of the vane geometry, and one integer variable representing the number of vanes for the structure.
Problem 5 is a weight minimization problem. This is formulated similarly to the stiffness maximization problem as:

$$\min_{\mathbf{G}_\mathrm{p}} \quad W(\mathbf{G}_\mathrm{p}) \tag{2}$$

Subject to $\mathbf{G}_\mathrm{lower} \leq \mathbf{G}_\mathrm{p} \leq \mathbf{G}_\mathrm{upper}$,
where W is the weight of the structure, and $\mathbf{G}_\mathrm{p}$ is the vector of geometrical design variables. As in the formulation for maximizing interface stiffness, $\mathbf{G}_\mathrm{lower}$ and $\mathbf{G}_\mathrm{upper}$ represent the lower and upper bounds on the geometrical design variables. The weight of the structure W varies depending on the design variables.

3.2 Results

All loading scenarios were solved in ANSYS v14.0. The individual optimization problems were solved using the mesh adaptive direct search algorithm (Le Digabel and Tribes, 2009; Le Digabel, 2011). Problems 1 to 9 were solved separately to obtain individual optima. The results are shown in Table 1. It can be noted that the majority of design variables are at either upper or lower bounds. For instance, all optimal values for problem 1 and 5 are at their bounds. Optimal values other than lower or upper bounds are found mostly for design variables b, c, d and h. Therefore, if a compromise solution is to be found, the compromise needs to be among these design variables. Some of the problems that have the same optimal values for the design variables can also be eliminated. For instance, problems 1 to 4 have virtually the same optimal values: only one problem needs to be considered as a representative of all the problems. We consider problems 5 and 6 to find a compromise solution applicable to all other problems.

Table 1. Results from optimising individual problems, problems 1 to 9 in Figure 4

	a*	b*	c*	d*	e*	f*	g*	h*	i*
Problem 1	green	green	green	green	green	red	green	red	red
Problem 2	green	blue	green	green	green	red	green	blue	red
Problem 3	green	green	blue	green	green	red	green	red	red
Problem 4	green	green	green	blue	green	red	green	blue	red
Problem 5	red	green	red	green	red	green	red	green	green
Problem 6	green	green	blue	purple	green	green	green	purple	red
Problem 7	green	purple	green	cyan	green	green	green	green	red
Problem 8	green	cyan	green	green	green	green	green	red	red
Problem 9	green	purple	green	cyan	green	green	green	green	red

- green: Optimum at *lower* bound
- red: Optimum at *upper* bound
- blue, cyan, purple: Optimum between bounds

3.3 Coordinated optimization

The purpose of the coordinated optimization is to find a compromise solution for problems 5 and 6 that will be applicable to all other problems. We used the non-hierarchical analytical target cascading (NHATC) coordination method (Tosserams et al., 2010) to find a compromise solution between the two competing problems. Since the different problems shown in Figure 4 are on the same structure, the coordination problem is essentially a multi-objective optimization problem. Kang et al. (2014) have demonstrated the application of NHATC to multi-objective optimization problems for design of vehicular systems.

Problems 5 and 6 are linked by the existence of local copies of the variables $\mathbf{G}_5$ and $\mathbf{G}_6$, which are coordinated by means of a penalty function. The two optimization problems are reformulated as:

$$\min_{\mathbf{G}_5} \quad \frac{W(\mathbf{G}_5)}{W_{nom}} + \mathbf{v}_{56}^{\mathbf{T}}\,(\mathbf{G}_5 - \mathbf{G}_6) + \|\mathbf{w}_{56} \circ (\mathbf{G}_5 - \mathbf{G}_6)\|_2^2 \tag{3}$$

Subject to $\mathbf{G}_{\text{lower}} \leq \mathbf{G}_5 \leq \mathbf{G}_{\text{upper}}$ and

$$\min_{\mathbf{G}_6} \quad \frac{K_6(\mathbf{G}_6)}{K_{6nom}} + \mathbf{v}_{56}^{\mathbf{T}}\,(\mathbf{G}_5 - \mathbf{G}_6) + \|\mathbf{w}_{56} \circ (\mathbf{G}_5 - \mathbf{G}_6)\|_2^2 \tag{4}$$

Subject to $\mathbf{G}_{\text{lower}} \leq \mathbf{G}_6 \leq \mathbf{G}_{\text{upper}}$.

In Equation (3), W is the weight of the load carrying configuration for problem 5 and W_{nom} is the nominal weight. Here, $W_{nom} = 700$ kg. $\mathbf{v}_{56}$ and $\mathbf{w}_{56}$ are the linear and quadratic weights associated with each coordinated variable. The symbol o denotes the Hadamard product (component-wise multiplication). $\mathbf{G}_6$ is the last vector of optimal design variable values obtained by solving problem 6, and is a parameter that problem 5 needs to match by varying the design variable $\mathbf{G}_5$.

In Equation (4), K_6 is the stiffness of the load-carrying configuration for problem 6, and K_{6nom} is the nominal stiffness. Here, $K_{6nom} = 1\text{E}9$ N/m. $\mathbf{G}_5$ is the last vector of optimal design variable values of problem 5, and is a parameter that problem 6 needs to match by varying the design variables $\mathbf{G}_6$.

After solving the individual problems, a convergence check is performed (the norm of the difference of solutions between problem 5 and 6 be less than a pre-specified value). If the convergence check fails, the coordination weights are updated and individual problems are solved again with the updated weights. The starting points for the individual problems will be the results from the previous solutions. This process is continued until convergence is achieved, i.e. when the design variables in the individual problems 5 and 6 agree with each other.

4 DISCUSSION AND CONCLUSION

Results from the optimization coordination problem discussed in Section 3.3 is shown in Figure 4. The LCC in (a) represents the starting point for the optimization, and the LCC in (b) represents the optimized result. The LCCs in (c) and (d) represent the solutions from individual optimizations for problems 5 and 6, respectively. It can be observed that the positions of points 4, 5, 6 and 7 (interface positions of the LCC, refer to Figure 3) in (b) lie between the positions for points 4, 5, 6 and 7 for (c) and (d). Thus, the result from the coordination problem is a compromise between the individual solutions for problems 5 and 6.

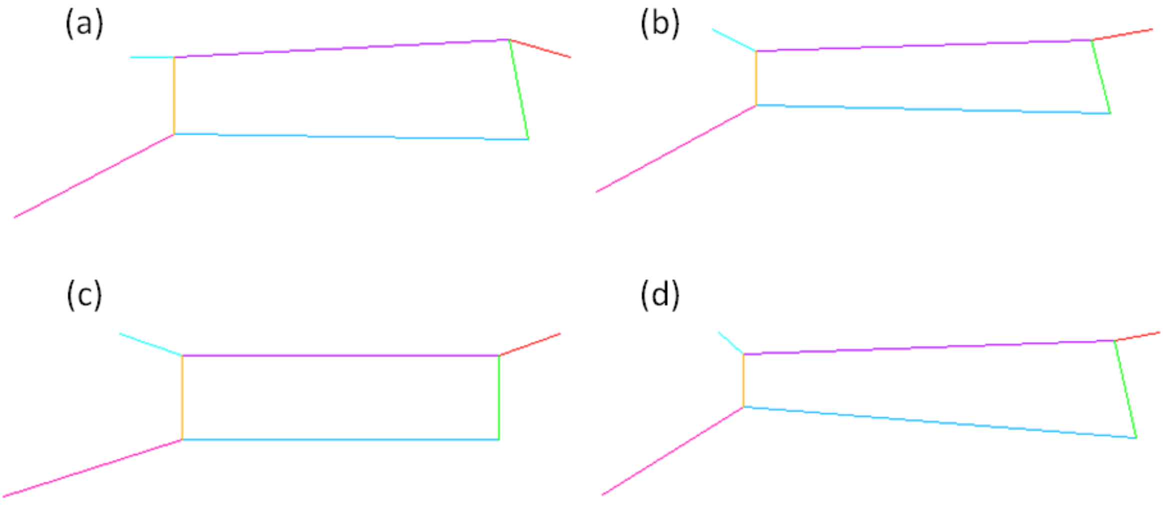

Figure 5. (a) Starting LCC (b) Optimized LCC after 2-problem coordination (c) Individual optimum for problem 5 (d) Individual optimum for problem 6

In this paper, we addressed the problem of providing early architecture decisions for integrated aero engine component such as an engine static structure. We considered one out of two aspects of the product's architecture, a mechanical load path (the other aspect is a gas flow path), to be optimized for different loading scenarios. The mechanical load path was represented as a load carrying configuration or LCC (see Section 2 for details) and the geometry of the LCC was optimized in two stages. In the first stage, from the optimization results for a number of loading scenarios on the LCCs, two loading scenarios were down selected. In the second stage, the down selected loading scenarios were run through an optimization coordination method called non hierarchical analytical target cascading (NHATC) to obtain a compromise solution that sufficiently satisfies all the loading scenarios on the LCCs. This single solution obtained for the LCC can be the basis for constructing detailed geometry for further analysis on the static structure. Also, the geometrical coordinates for the LCC represent the allowable volume for eventual (or concurrent) aero-thermodynamic design for the flow path for the structure. Thus, this paper demonstrated the applicability of an optimization coordination method for multidisciplinary design optimization to early architecture selection of integrated aero engine components.
The study is limited in that only one LCC is considered. More realistic studies will consider several options for the LCCs and loading scenarios, which makes the selection of an appropriate mechanical load path for the structure difficult. A methodical approach such as the one we presented could facilitate faster selection of suitable product architectures. The LCC optimization does not consider any constraints other than the upper and lower bounds of the design variables. The analyses consider only the bare minimum of geometry, which makes the results valid only for preliminary design reviews. Even though the problem presented here is idealized, it satisfactorily represents the considerations around architectural decisions for individual engine components corresponding to overall engine architecture choices.
Future implementation of the problem will involve adding a number of LCCs in addition to the ones considered here, as well as other analysis disciplines that impose constraints on the structure. In this paper, we considered only one discipline, namely structural analyses. Addition of other disciplines makes the integrated product architecture selection a much larger problem and coordination among individual formulations will be critical in deciding a good architecture. Our approach is believed to serve as a robust starting point for addressing such problems in the industry.

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