
Thesis Proposal

Revised

CAD-Based Multifidelity Analysis and Multidisciplinary Optimization in Aircraft Conceptual Design

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Abstract

The conceptual and preliminary phases of modern aircraft design methodologies exhibit a gap in analysis and geometry fidelity. In conceptual design, low-fidelity multidisciplinary tools are generally used with an accompanying abstract description of the aircraft configuration, typified by configuration parameters of the design planform. In preliminary design and beyond, however, higher-fidelity multidisciplinary analysis is used to completely design the aircraft components and a three-dimensional (3D) solid model becomes a necessity. The methodological gap exists between these two independent realms of analysis and two very distinct geometry representations. By not having a consistent geometry definition across all design phases, the multidisciplinary results from earlier design phases do not become strictly transferable to the later analysis of a fully-defined configuration geometry. Some aspects of new configurations may only be understood through the analysis of higher-fidelity geometry, yet remedies need to occur in the conceptual design phase in order to avoid costly engineering work-arounds. A bridge across the methodological gap is proposed herein by enabling multifidelity analysis in conceptual design with a single consistent 3D geometry that encapsulates the multifidelity parameter space of multidisciplinary analysis codes. This improved design methodology centralizes geometry information into a single model and permits multidisciplinary analysis codes of varying fidelity to extract configuration details from the *same* model. In addition, this methodology is enhanced by applying it to gradient-based optimization. Work is proposed herein to accomplish this by investigating design velocity calculation methods for 3D models that are both multidisciplinary and multifidelity. Studies focused on incorporating multifidelity configuration parameter sensitivities into multidisciplinary performance sensitivities are also proposed. The combination of these methods will bridge the methodological gap found currently in aircraft design processes.

Contents

Abstract	1
1 Introduction	3
1.1 Motivation for Bridging the Gap Across Design Phases	4
1.2 Applying Gradient-Based Optimization	5
1.3 Terminology	5
2 State-of-the-Art in Multifidelity MDO and Conceptual Design	8
2.1 Conceptual Design Methodology	8
2.2 Multifidelity Analysis in MDO	9
2.2.1 Parametric Geometry Generation	10
2.2.2 Automated Data Transfer Between Tools	10
2.2.3 Automated High-Fidelity Analysis	11
2.2.4 MDO	11
2.3 Sensitivity Calculation for CAD-based Optimization	12
2.3.1 Common Sensitivity Methods	12
2.3.2 Shape Sensitivity Analysis	14
3 Open Conceptual Design Issues	18
3.1 Conceptual Design Methodology	18
3.2 CAD-based Shape Sensitivity Analysis	20
4 Proposed Research	21
4.1 Research Objectives	21
4.2 General Research Approach	22
4.2.1 Geometry and Parametric Model Management for Multifidelity Design	22
4.2.2 Determining the Design Velocity of Multifidelity Geometry	23
4.2.3 Relating Multifidelity Parameter Sensitivities to Performance Sensitivity	23
4.3 Summary of Current Work	24
5 Expected Contributions	28
6 Research Timeline	29
References	30

1 Introduction

AIRCRAFT conceptual design methodologies evolved throughout the last 100 years with the advent of improved design tools: from trial-and-error experimentation with the Wright Brothers, to sophisticated multidisciplinary optimization (MDO) suites containing empirical analysis tools, followed by detailed design packages utilizing high-fidelity computational fluid dynamics (CFD). Tam acknowledges this growth as moving from an “Edisonian” era, where experimentation was required due to little known theory, to analysis-and-test, followed by physics-based modeling and simulation [1]. Other factors molded the design methodologies as well, namely scheduling constraints, design objectives, experience and available analysis fidelity [1].

A commonly accepted organizational setup spans the design methodologies used today, as illustrated later in Figure 2.1. This framework is primarily divided into the following three phases:

1. **Conceptual design**, where the initial aircraft concept planform is defined;
2. **Preliminary design**, where trade studies are conducted on a fixed planform configuration expressed as a wireframe or 3D model;
3. **Detailed design**, where all detailed specifications are defined for every aircraft component using a discipline-specific 3D solid model (typically within a Computer Aided Design (CAD) system).

Conceptual design is a unique phase in comparison to preliminary or detailed design phases. Typically scheduling constraints—on the order of weeks or a month—permit evaluation of only a few concepts using low-fidelity MDO tools [2, 3]. Empirically derived data and carpet plots are often also utilized to properly size a configuration. Even though these methods yield results in relatively short computational time, they serve only as zeroth- or first-order estimates of performance for later design phases to improve upon. The low-fidelity methods also rely exclusively on configuration parameters to describe the aircraft planform. A fully-parameterized, realizable 3D model of the aircraft configuration usually does not exist in this design phase.

High-fidelity multidisciplinary analysis becomes the norm in preliminary and detailed design phases, as evidenced by an immense library of CFD and finite-element analysis (FEA) research literature. Such tools are based on physical principles modeling various flow regimes, structural complexity and established control laws. There is typically greater confidence in the results stemming from high-fidelity analysis compared to low-fidelity analysis, yet there accompanies longer computational time and a need for fully-defined, 3D models of the aircraft components. The 3D models must include component assembly information, surface definitions (e.g., span-wise airfoil distribution) and structural layout [4, 5]. Discipline-specific CAD models are generally used in the detailed design phase to define these geometric details. A computational domain for CFD and FEA is then obtained by tessellating the models into a surface or body mesh via a meshing algorithm.

1.1 Motivation for Bridging the Gap Across Design Phases

The methodology described above is generally the *de facto* process applied in industry. However, attempting to use high-fidelity multidisciplinary analysis in a conceptual design setting reveals the need for a different design methodology. Current design methods create a methodological gap by spreading multifidelity analysis codes of various disciplines across design phases. These analysis codes rely on particular geometry representations that are inconsistent across each phase due to varying fidelity:

1. **Conceptual Design Geometry:** a non-realizable set of configuration parameters that define the major components of the aircraft planform (note that *configuration parameters* refer to parameters defining the aircraft planform, which contrasts with parameters that dimension a geometric primitive);
2. **Detailed Design Geometry:** an analytical solid model or CAD model that provides a fully-realizable 3D description of the aircraft and its components.

By bridging this gap, conceptual design can embrace high-fidelity multidisciplinary analysis alongside low-fidelity tools by using a 3D geometry representation that is both multidisciplinary and multifidelity.

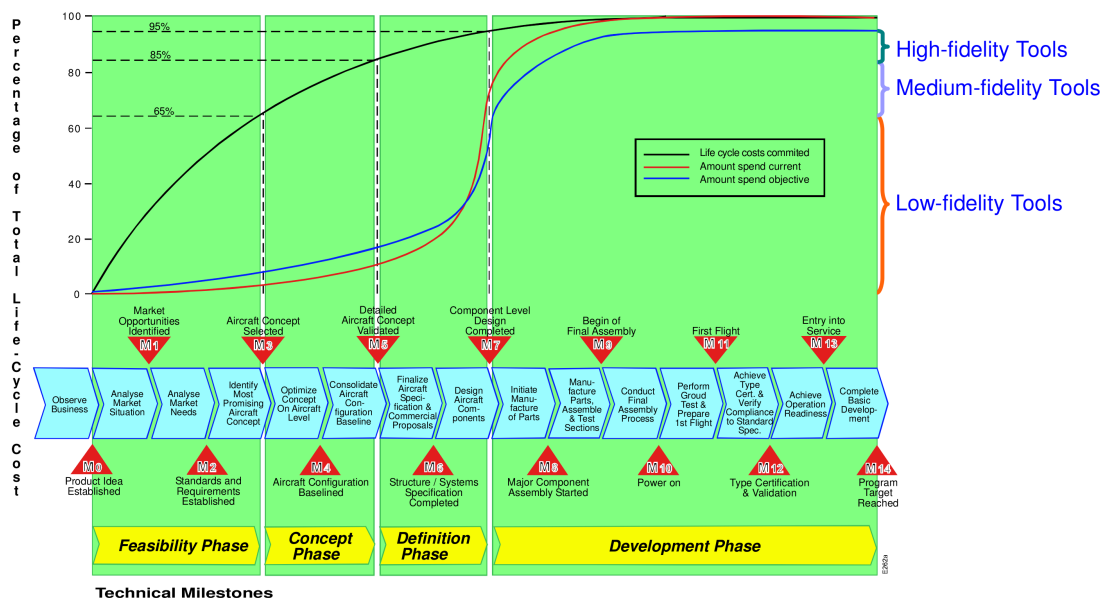


Figure 1.1: A plot of relative total Life-Cycle Cost in the various aircraft lifecycle phases (plot taken directly from Kessler’s work in [6]).

Even though current design methodologies successfully created the aircraft now in service, the methodological gap will lead to costly flaws when more stringent scheduling constraints demand shorter design times. For example, due to the inverse proportionality of design knowledge to committed aircraft life-cycle program costs, as reported by Kessler, 65%

of the program costs are often committed by the time a concept is selected at the end of conceptual design [6, 7, 8, 9]; as highlighted in Figure 1.1, it is clear that low-fidelity analysis and geometry are typically the sole tools used to establish that cost commitment. In addition, the empirical nature of low-fidelity analysis limits its applicability to previous design types (e.g., tube-and-wing configurations); extrapolation of low-fidelity trends for new configurations or new technologies is generally less-effective as well. Advancing high-fidelity analysis and geometry into the conceptual design phase will likely eliminate these issues and reduce the future cost of implementing engineering work-arounds to a new configuration [10, 11].

1.2 Applying Gradient-Based Optimization

By bridging the methodological gap with 3D models that are both multidisciplinary and multifidelity, an enhanced application is possible by implementing gradient-based optimization. The impact of 3D model configuration parameters on performance sensitivity metrics becomes necessary. Much work, using two particular ideologies, has been done in the structural analysis community to address this issue:

1. **CAD-free design:** This approach uses analytical formulations of a 3D model, such as NURBS surfaces, and allows for control of topology. Differentiation of the operators used to create the final surface is possible, thus allowing for efficient sensitivity calculations on a surface.
2. **CAD-based design:** The 3D model is created within a CAD system via a series of geometric operations, captured as a history in a feature-tree. Although complex, parameterized 3D models can be created in these systems, the underlying analytical formulation is hidden in the proprietary source code. Differencing, for example, is done for sensitivity calculations using a baseline tessellation and a tessellation generated from a perturbed 3D model.

The underlying shape sensitivity analysis determines the coupling between faces defining the 3D model to the configuration parameters driving the overall design. Various methods exist to accomplish this, yet each tailors to a specific model representation and experience certain limitations. Such limitations have hindered the utilization of CAD-based, multifidelity analysis in MDO due to increased computational time and errors in the determination of parameter sensitivity. This proposal outlines a set of research goals that will attempt to reduce the computational time for determining sensitivities with increased accuracy and robustness.

1.3 Terminology

To ensure that terminology in this proposal is consistent, clarification of the terms CAD-free, CAD-based, analysis fidelity and multifidelity MDO are given. First, in regards to 3D model geometry, Figure 1.2 illustrates the differences between CAD-free and CAD-based geometry.

Both are capable of producing 3D geometry; however, 3D models from a CAD system are defined distinctively as CAD-based.

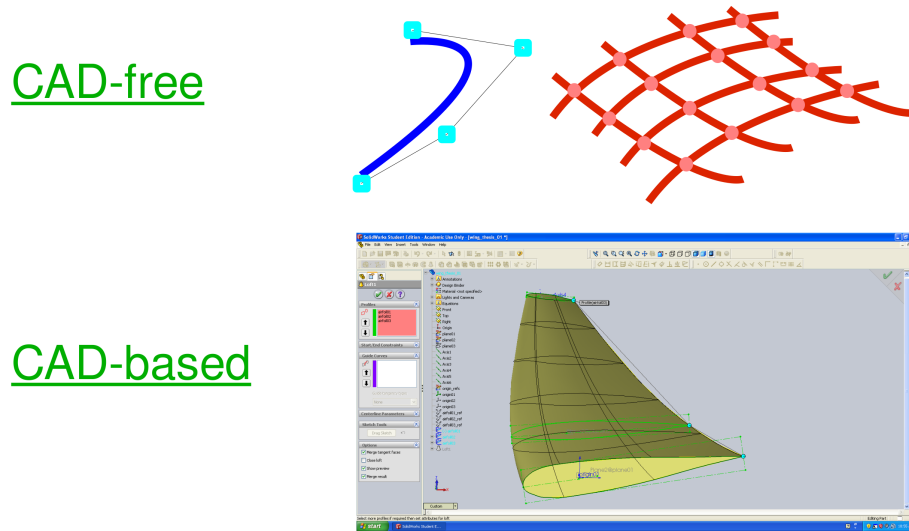


Figure 1.2: Illustration of differences in geometry as seen in a CAD-free and CAD-based context.

In addition, various fidelity levels are possible in multidisciplinary analysis. As seen in Figure 1.3, a summary of various reasons dictate that analysis be categorized as low-, medium- or high-fidelity.

Finally, using multifidelity analysis in MDO is understood to comply with Figure 1.4. The analysis codes providing objective function evaluations or constraint calculations may have distinguishing levels of fidelity, or the same fidelity.

Low-fidelity	Medium-fidelity	High-fidelity
<ul style="list-style-type: none"> • Empirical & Statistical Analysis 	<ul style="list-style-type: none"> • Physics-based, linear/non-linear analysis 	<ul style="list-style-type: none"> • Physics-based, linear/non-linear analysis
<ul style="list-style-type: none"> • High-level configuration parameters 	<ul style="list-style-type: none"> • High-level configuration parameters • 3D location of major components • General structural information 	<ul style="list-style-type: none"> • Geometry of detailed surface contours • Body mesh of detailed internal structural components
<ul style="list-style-type: none"> • Parameter space DOF < 100 	<ul style="list-style-type: none"> • Parameter space DOF ~ 100 or greater 	<ul style="list-style-type: none"> • Body or surface tessellation node DOF ~ 10^5 to 10^6

Figure 1.3: A table illustrated with distinguishing features of low-, medium- and high-fidelity multidisciplinary analysis.

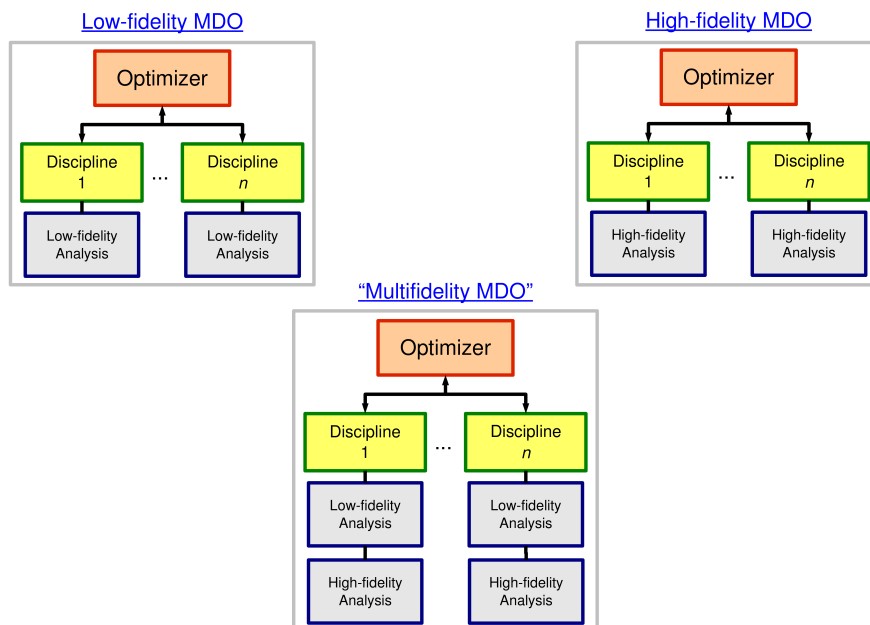


Figure 1.4: A categorical depiction of various fidelity analysis possible in a MDO setting.

2 State-of-the-Art in Multifidelity MDO and Conceptual Design

A summary of research is presented here to establish the current technology and methodologies used in aircraft conceptual design. First, methodologies and tools often incorporated in the conceptual design phase are explained. Secondly, an overview of work done in the realm of MDO, including the implementation of high-fidelity analysis, is mentioned to emphasize the maturity of available methods. This provides motivation for including high-fidelity analysis in the MDO used in conceptual design. Lastly, in accordance with the proposed methodology of bridging the methodological gap using multidisciplinary, multifidelity 3D models, efforts for generating sensitivities of objective functions to 3D model configuration parameters are examined.

2.1 Conceptual Design Methodology

A typical design methodology in practice today is illustrated in Figure 2.1. In the greater scope of an aircraft life cycle, these phases are followed by the manufacture, testing, customer delivery, service and retirement of the aircraft configuration finalized in design.

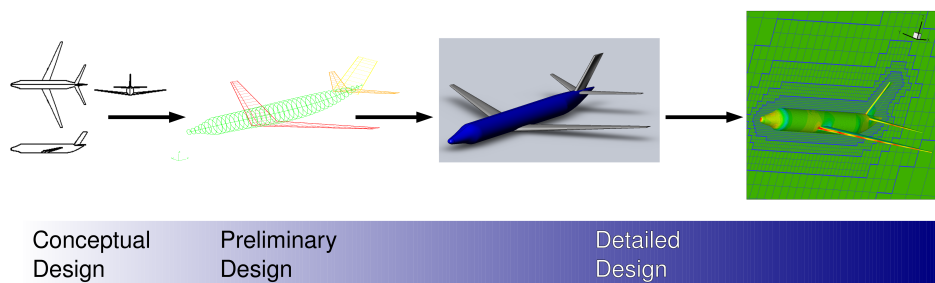


Figure 2.1: Evolution of the geometrical representation of an aircraft concept throughout a typical in-series design process.

During the conceptual design phase, design commences with a small set of simplified, high-level geometry parameters that size a concept aircraft, illustrated by the planform sketch of a configuration in Figure 2.1. Such parameters include wing area, wing aspect ratio, tail arm, wing taper ratio, wing sweep, fuselage length and radius, among many other options. This parameter set becomes the design variables for low-fidelity MDO, where empirical or statistical methods are predominantly used [12]. In addition, these parameters are associated with carpet plots, which help correlate the configuration sizing to mission performance. Configuration sizing is varied by an optimizer until customer-specified mission and constraint requirements are met. Due to the amorphous nature of the design, and numerous pending design decisions, Raymer [13] and others [14, 15, 16] suggest the use of simple drafting methods, or artist renderings, to transform the parameter representation into a recognizable configuration. Once in preliminary and detailed design phases, as seen

in Figure 2.1, the sketches are translated into wireframe and 3D models for medium- and high-fidelity analysis, respectively.

Many low-fidelity codes exist for conceptual design. An early example was Design Sheet [17], which permitted trade studies, optimization and sensitivity analysis using algebraic equations relating the configuration design parameters to performance metrics. Kroo et al. developed a modern low-fidelity MDO framework in Java called the Program for Aircraft Synthesis Studies (PASS) [18, 19], which utilizes empirical models for performance calculations, contains an internal simplex and genetic algorithm (GA) optimizer and uses configuration-level descriptors of an aircraft. Drela’s ASWING [20] is an efficient medium-fidelity FORTRAN code that couples lifting-line and vortex-lattice aerodynamic modeling with a nonuniform, nonlinear structural formulation. The physical dimensioning and location of lifting surfaces and fuselage is required to conduct analysis in ASWING. This code permits quick redesign and analysis without an automated optimizer.

A different methodology was instituted in Design and Engineering Engine (DEE), created at the Delft Institute of Technology. DEE was developed to experiment with a Knowledge Based engineering approach to conceptual design [21]. This design framework was founded on the idea of having a central aircraft model contain the data transmitted to all design phases and analysis disciplines, in contrast to the design phase executed in series seen in Figure 2.1. Crawford et al. used a similar methodology in the design of a wind turbine [22].

Amadori et al. [5, 4] and Jounnet et al. [12] are part of a large development in improving conceptual design methodology via a new web-services, CAD-based MDO framework. Their work encompasses the notion that empirical or statistical methods are appropriate in sizing aircraft, yet should not be the sole means of providing performance results. They point out that such methods cannot be extrapolated to analyze unconventional configurations, or configurations dissimilar to those used in creating the empirical methods.

Amadori et al. also recognized, as did others [22], the need to have parameterized 3D models that would regenerate successfully throughout a continuous set of configuration parameters. In their work, automatic creation of the 3D models in CAD was important in order to avoid the tedious manual process. Although their CAD model contained parameterized configuration data used by the optimizer, their panel code aerodynamics module utilized a separate surface mesh until further development permitted tessellating the CAD model directly [4]. Since their MDO work utilized heuristic methods instead of gradient-based optimizers, sensitivities were not calculated using the 3D model. Takenaka et al. [23] also utilized a GA with MDO to avoid the task of calculating sensitivities when employing Euler and Navier-Stokes flow modeling, along with high-fidelity NASTRAN analysis.

2.2 Multifidelity Analysis in MDO

After recognizing the need for evolving conceptual design methods, with an emphasis on utilizing high-fidelity analysis in MDO, Bowcutt indicated in [10] that the following advanced design technologies were needed:

- Parametric geometry generation

- Automated data transfer between tools
- Automated high-fidelity analysis
- MDO
- Probabilistic tools for systems-level risk assessment, uncertainty-based optimization
- Collaborative/distributed/grid computing
- Quantify system effectiveness by modeling development, manufacturing, operations and campaign use

The first four items above are of particular relevance to this work and are elaborated upon below.

2.2.1 Parametric Geometry Generation

The call for parametric geometry generation makes reference to a 3D model representation of an aircraft under a driving set of configuration parameters, such as wing area, aspect ratio and fuselage radius. This parameterized model is expected to regenerate within a predefined, bounded parameter set of continuous configuration parameters. A 3D model satisfies this requirement if the set of aircraft configuration parameters drives its design intent. Crawford et al. [22] accomplished this with wind turbine design. Even though the use of CAD tools is well established in industry through products such as SolidWorks, Pro/Engineer, Unigraphics, CATIA, etc.; nevertheless, traditional drafting practices are not entirely suitable for properly creating multidisciplinary 3D models that have multifidelity configuration parameter spaces. Also, automatic 3D model generation is possible, as done in [4, 5]; yet, care must be taken with the design intent.

Parameterization options have also been studied. Kulfan, besides providing parameterization for common aircraft configuration components, points out that the chosen parameterization greatly impacts the MDO scheme utilized, depending on the number of design variables, geometric representation and possibility of design smoothness or irregularity throughout the design space [24, 25]. Many applications of MDO in the literature represent varied parameterizations that are unique to the problem at hand, as found in [26, 27, 28, 12, 29]. The shape optimization community also provides a large span of parameterization choices. Configuration parameters, airfoil shape functions, NURBS surfaces, lines, conic sections, splines, algebraic curves, four-point curves, Bezier curves, and B-spline curves all contain different parameterization options. Various examples of parameterization in shape optimization are found in these references: [30, 31, 32, 33, 34, 35, 36, 37, 38, 39, 40, 41, 42, 43].

2.2.2 Automated Data Transfer Between Tools

A second issue surrounding utilization of high-fidelity analysis in MDO is the automatic data transfer between tools. Since each analysis tool, regardless of fidelity, is typically compiled

as a stand-alone application, their associated input/output (IO) scheme is incompatible with other analysis tools, especially if tools were created with different programming languages. Either IO files or an XML database may link multifidelity tools. A web-services approach at handling data flow was attempted by Amadori et al. and Jouannet [4, 12]. In the case of Hwang et al. [44], Oracle databases were utilized in their Multidisciplinary Aircraft Design and Evaluation (MADE) software to allow for efficient data storage and retrieval. Takenaka et al. [23] used an in-house interfacing code to provide communication between aerodynamic and structures analysis codes. An understanding of the data transmitted between an optimizer and multifidelity tools is paramount to minimize data-flow bottlenecks. ModelCenter [45] and iSight [46] are both environments aimed at simplifying the automation of data transfer between analysis codes used in MDO. Users specify the IO scheme for each analysis code and an internal optimizer routes appropriate data to corresponding analysis modules.

2.2.3 Automated High-Fidelity Analysis

Thirdly, automated high-fidelity analysis implicitly refers to both quality mesh creation and analysis execution. Historically, difficulty lies in the manual inspection of meshes in order to determine, and likewise correct, the element quality, water-tightness and resolution of particular geometrical entities of interest. Today packages such as Cart3D, created by Aftosmis et al. [47], handle automated mesh generation for CFD analysis via an input tessellation of the surface geometry. Cart3D is an Euler solver that is executable via simple scripts, wherein a surface tessellation input file is used to automatically create cartesian meshes for the flow solver. The capability of automated tessellation is also possible through the Computational Analysis PRogramming Interface (CAPRI) API [48, 49]. Cart3D creates volume meshes based on user-defined metrics and CAPRI controls body tessellations corresponding to another set of user-defined quality metrics.

2.2.4 MDO

Lastly, advances in MDO span a large field of current research. In regards to optimization methods, both gradient-based, such as sequential quadratic programming (SQP), and heuristic methods, such as GA, have evolved substantially through the work found in numerous publications. Zang et al. [50] provides an extensive survey of MDO work in the context of fluid dynamics research and identifies the need for further research on variable-fidelity analysis in MDO. In order to limit the computational cost of high-fidelity codes, Balabanov et al. demonstrated medium- or high-fidelity objective function evaluations with low-fidelity gradients in [51]. In [52] Robinson utilized surrogate-based optimization to address the issue of high-fidelity computational time and also provided a mapping between design variable spaces of different length when using two or more varying fidelity codes. Work in trust-region model management (TRMM) [53] has also shown to reduce computational time by quantitatively determining when to use low-fidelity models as a surrogate for high-fidelity analysis in a region of the design space.

The application of multifidelity analysis in MDO is a topic of growing interest in academic

circles [50]. Carty et al. [54] and Bowcutt [10] have both determined that, when MDO is implemented, designers tend to have greater trust in the performance results of an aircraft if high-fidelity codes are used (also see Zang et al. [50] and Haimes et al. [11] for statements on cultural adaptations required by organizations implementing MDO). This mentality stems from the fact that the current design process qualifies low-fidelity results only after high-fidelity analysis offer confirmation. Vandenbrande et al. [3] favored the use of high-fidelity analysis in MDO because aircraft configuration issues were resolved much earlier in the design process. Through their development of the Boeing General Geometry Generator (GGG), they found a 50% design objective improvement of radically new designs, 10% improvement of novel designs and 2% improvement of mature designs.

Other frameworks aimed at simplifying the implementation of high-fidelity analysis in MDO include the following:

- Boeing MDOPT
- π MDO
- DEE

Boeing’s MDOPT is an example of a modern MDO framework that contains preset discipline solvers, such as multifidelity flow and structural solvers, that act as black-boxes to the user [55]. π MDO attempts to simplify the implementation of multifidelity analysis in MDO with a Python software environment using object-oriented programming [56].

DEE, introduced above in [21], also exhibits the capability of implementing multifidelity analysis in MDO by permitting disciplinary experts to use their custom code modules for analysis. Various aircraft classes and derivative designs are automatically created by an internal geometry generator from a set of predefined components. A similar framework, under development by Amadori et al. [4, 5] and Jounnet et al. [12], also uses a modular, distributed web-services approach with low- and medium-fidelity codes and automatic CAD model generation.

2.3 Sensitivity Calculation for CAD-based Optimization

In this section a short summary of analytical, CAD-free and CAD-based design sensitivity calculation methods are presented from the literature. Methods utilized by most researchers are presented first, followed by different implementations of shape sensitivity analysis.

2.3.1 Common Sensitivity Methods

The calculation of objective function sensitivity to configuration parameters is crucial for gradient-based optimization. By no means is this a new area of research, as evidenced by numerous publications that utilize some form of sensitivity calculation in a flow or structures solver. Sensitivities are easily calculated if, for example, an analytical expression exists for a C^0 -smooth, integral objective function $F = \int_{\Omega} f d\Omega$ over a domain Ω in \mathfrak{R}^3 , where f is a

function of \mathbf{x} , the vector of design variables, and \mathbf{U} , a CFD flow solution. For that matter, if F is C^1 -smooth, the Hessian is also easily determined. When such relationships exist, or the feature-based sequence of solid model construction is available via CAD-free, or variational, geometry methods, this method is clearly preferred above all others. Chen and Tortorelli [31] provided sensitivities using a solid model that utilized variational geometry, thereby permitting implicit or parametric approaches to calculating the design velocity (defined below).

Geometric representation greatly influences the method in which sensitivities are determined. Fudge et al. [57] provided a comparison of the advantages and disadvantages surrounding both CAD-free approaches and CAD-based methods in gradient-based optimization. In CAD-free frameworks, where a majority of shape optimization research has been conducted, analytical representations existed for the domain definition or a surface triangulation was used with finite-differencing or adjoint methods. Some examples include the use of Free-From Deformation (FFD) techniques, as done by Samareh [41], shape functions for airfoil approximation, as presented by Hicks and Henne [58], basis vectors [59], domain element approach, partial differential equations [60], discrete approach [61, 62] and polynomial/spline approaches [63, 3]. Other methods, such as the level-set method and various forms of topology optimization (topological derivative and adjoints) are discussed in references [64] and [38, 65], respectively.

In other references a CAD model was tessellated, as found in [36, 11, 66, 34, 35, 39, 67, 37]. For example, in the case of finite-differencing, the mesher tags each node of a baseline surface mesh, thereby maintaining associativity of the nodes with respect to edges and faces of the model (via (u, v) parameters). As design parameters are perturbed, the mesh is deformed by repositioning the baseline nodes. The sensitivity of the nodes to the parameter perturbation is determined by differencing the new and old (x, y, z) coordinates of the nodes projected on the associated face or edge. This is often called the surface mesh sensitivity to the parameters, $\frac{\partial \mathbf{S}}{\partial \mathbf{x}}$, where \mathbf{S} is the surface mesh and \mathbf{x} are the parameters. An important assumption in this method is that the model topology does not change; otherwise, remeshing is required of new instances in order to avoid solutions obtained from a badly deformed mesh. In addition, when a volume mesh, \mathbf{V} , is used by a CFD code, sensitivity of the volume mesh to the surface mesh is required: $\frac{\partial \mathbf{V}}{\partial \mathbf{S}}$. The sensitivity of the CFD solution, \mathbf{U} , to the volume mesh is usually determined by adjoint methods as well: $\frac{\partial \mathbf{U}}{\partial \mathbf{V}}$. Finally, the sensitivity of the objective function, F , to the CFD solution is required ($\frac{\partial F}{\partial \mathbf{U}}$) to complete the sensitivity calculation, as found in Zang [50]:

$$\frac{\partial F}{\partial \mathbf{x}} = \underbrace{\frac{\partial F}{\partial \mathbf{U}}}_1 \cdot \underbrace{\frac{\partial \mathbf{U}}{\partial \mathbf{V}}}_2 \cdot \underbrace{\frac{\partial \mathbf{V}}{\partial \mathbf{S}}}_3 \cdot \underbrace{\frac{\partial \mathbf{S}}{\partial \mathbf{x}}}_4. \quad (2.1)$$

1. Objective sensitivity to the solution
2. Solution sensitivity to the volume mesh
3. Volume mesh sensitivity to the surface mesh
4. Surface mesh sensitivity to the configuration parameters

The different terms in equation (2.1) are labeled to indicate which sensitivities they represent. Adjoint CFD solvers can provide sensitivity information for all partial derivatives in equation (2.1) except $\frac{\partial \mathcal{S}}{\partial \mathbf{x}}$.

2.3.2 Shape Sensitivity Analysis

Zang et al. pointed out that, at the time of their publication, there was no analytical method for extracting CAD model surface sensitivities with respect to the model parameters [50]. Due to the fact that CAD developers have not included such a feature in their CAD systems, the calculation of surface sensitivities for a parameterized domain is a topic of current research, much of which is conducted in the structures community for finite element meshes, and discussed below.

Haimes et al. [11], and others, have found that automatic differentiation (as available using codes such as ADIFOR [68] and ADIC [69]) of entire CAD systems would be an intractable process if the source code is unavailable. Some researchers prefer developing an in-house CAD system, albeit limited in scope and requiring constant expansion to accommodate for greater design flexibility; the great advantage, though, is that the code is differentiable. Such was the case in work done by Kleinveld et al. [67].

Other researchers have utilized variants of shape sensitivity analysis to bypass the need for a differentiated CAD system. Choi and Kim present a derivation of shape sensitivity analysis as follows (from [43]):

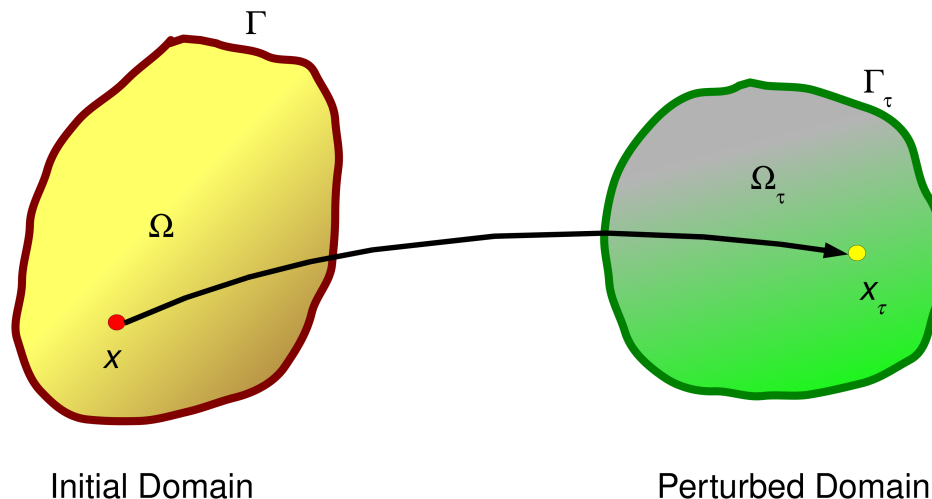


Figure 2.2: An illustration of domain perturbation by a mapping \mathbf{T} in shape sensitivity analysis.

As seen in Figure 2.2, an initial domain, Ω , is perturbed and becomes a new domain, Ω_τ , via a transformation \mathbf{T} . A point, \mathbf{x} , in domain Ω is also mapped into the new domain as

\mathbf{x}_τ , where $\mathbf{T} : \mathbf{x} \rightarrow \mathbf{x}_\tau(\mathbf{x})$, $\mathbf{x} \in \Omega$. τ can be considered a design time. Therefore,

$$\begin{aligned}\mathbf{x}_\tau &= \mathbf{T}(\mathbf{x}, \tau), \\ \Omega_\tau &= \mathbf{T}(\Omega, \tau).\end{aligned}$$

A design velocity can then be constructed as

$$\vec{\mathbf{V}}(\mathbf{x}_\tau, \tau) \equiv \frac{d\mathbf{x}_\tau}{d\tau} = \frac{d\mathbf{T}(\mathbf{x}, \tau)}{d\tau} = \frac{\partial \mathbf{T}(\mathbf{x}, \tau)}{\partial \tau}. \quad (2.2)$$

The last equality holds since the first design point, \mathbf{x} , does not depend on τ . If \mathbf{T} is given, it is possible to solve for $\vec{\mathbf{V}}$; otherwise, an initial-value problem must be solved

$$\begin{aligned}\dot{\mathbf{x}}_\tau &= \vec{\mathbf{V}}(\mathbf{x}_\tau, \tau), \\ \mathbf{x}_0 &= \mathbf{x}.\end{aligned}$$

Without a given transformation, and a regularity assumption is made for the neighborhood of $\tau = 0$, \mathbf{T} can be expanded with a Taylor series about $\mathbf{T}(\mathbf{x}, 0)$, with neglected higher-order terms:

$$\mathbf{T}(\mathbf{x}, \tau) = \mathbf{T}(\mathbf{x}, 0) + \tau \frac{\partial \mathbf{T}}{\partial \tau}(\mathbf{x}, 0) + \dots = \mathbf{x} + \tau \vec{\mathbf{V}}(\mathbf{x}, 0) + \dots \quad (2.3)$$

The linear mapping is then $\mathbf{T}(\mathbf{x}, \tau) = \mathbf{T}(\mathbf{x}, 0) = \mathbf{x} + \tau \vec{\mathbf{V}}(\mathbf{x})$, with $\vec{\mathbf{V}}(\mathbf{x}) = \vec{\mathbf{V}}(\mathbf{x}, 0)$. The regularity assumption presumes that the transformation, $\mathbf{T}(\mathbf{x}, \tau)$, is a one-to-one, continuous map with a continuous inverse (homeomorphism). This implies that Ω , a C^k -regular open set, has a boundary Γ that is closed and bounded in \mathbb{R}^n and can be piecewise represented as a C^k function (a compact manifold of C^k). In addition, the design velocity has continuous derivatives up to the order $k \geq 1$.

It is the determination of design velocity $\vec{\mathbf{V}}(\mathbf{x}, \tau)$ that is of crucial importance in calculating the sensitivity. Choi and Kim [43], Chen et al. [70] and Hardee et al. [40] each show the derivation of the objective function sensitivity to design parameters, which includes the importance of the design velocity. Belegundu et al. used a similar derivation while using natural design variables, where the magnitude of the design variables pertained to a set of fictitious loads applied to a structural domain [33]. These fictitious loads determined the domain displacement, or in the vernacular of shape optimization, domain perturbation. Essentially, as expressed in Chen et al. the geometric parameter b is selected for perturbation, hence $\Omega : b \rightarrow \Omega(b)$. With δb being a small perturbation in b , the new domain becomes $\Omega(b + \delta b)$. It is also assumed that a mapping exists, \mathbf{T} , such that $\mathbf{T} : \mathbf{x}(b) \rightarrow \mathbf{x}(b + \delta b)$; likewise, $\Omega(b + \delta b) = \mathbf{T}(\Omega(b); \delta b)$. This transformation also permits

$$\begin{aligned}\mathbf{x}(b + \delta b) &= \mathbf{T}(\mathbf{x}(b); \delta b) \\ &= \mathbf{T}(\mathbf{x}(b); 0) + \delta b \frac{\partial \mathbf{T}}{\partial \delta b}(\mathbf{x}(b); 0) + \mathcal{O}(\delta b^2) + \dots \\ &= \mathbf{x}(b) + \delta b \frac{d\mathbf{x}(b)}{db} + \mathcal{O}(\delta b^2) + \dots \\ &= \mathbf{x}(b) + \vec{\mathbf{V}} \delta b.\end{aligned} \quad (2.4)$$

In order to find the sensitivity of the functional F to this perturbation, the Jacobian of the transformation is required, namely $\mathbf{J} = \nabla \mathbf{T} = \mathbf{I} + \delta b \nabla \vec{\mathbf{V}}$. Thus, for an objective function $F(b) = \int_{\Omega(b)} f(b, \mathbf{x}(b)) d\Omega$, the perturbation creates

$$\begin{aligned} F(b + \delta b) &= \int_{\Omega(b + \delta b)} f(b + \delta b, \mathbf{x}(b + \delta b)) d\Omega \\ &= \int_{\Omega(b)} \left[f(b + \delta b, \mathbf{x}(b) + \vec{\mathbf{V}} \delta b) |\mathbf{J}| \right] d\Omega. \end{aligned}$$

Therefore, the sensitivity is found as

$$\begin{aligned} \frac{dF}{db} &= \int_{\Omega(b)} \left[\frac{df}{db} + f \frac{d|\mathbf{J}|}{db} \right] d\Omega \\ &= \int_{\Omega(b)} \left[\frac{\partial f}{\partial b} + \nabla f^T \cdot \vec{\mathbf{V}} + f \operatorname{div}(\vec{\mathbf{V}}) \right] d\Omega \\ &= \int_{\Omega(b)} \left[\frac{\partial f}{\partial b} + \operatorname{div}(f \vec{\mathbf{V}}) \right] d\Omega \\ &= \int_{\Omega(b)} \frac{\partial f}{\partial b} d\Omega + \int_{\partial\Omega(b)} f \vec{\mathbf{V}} \cdot n d\Gamma, \end{aligned} \tag{2.5}$$

where n is the surface normal. It is clear that only the design velocity on the *boundary* is required to determine the sensitivity, assuming that the partial derivative for $\frac{\partial f}{\partial b}$ can be found (either analytically or numerically). Even more so, only the normal component of $\vec{\mathbf{V}}$ is required. Chen et al. extend this derivation by claiming that the design velocity on the entire domain boundary Γ is not required; only the *active* portions of the boundary, those influenced directly by the perturbed geometric parameter b , need to be integrated over. Thus, the second term in equation (2.5) becomes

$$\int_{\partial\Omega(b)} f \vec{\mathbf{V}} \cdot n d\Gamma = \sum_{k \in \mathcal{A}(b)} \int_{\partial\Omega_k} f \vec{\mathbf{V}} \cdot n d\Gamma,$$

where k is the index to each active boundary (boundaries influenced by b) in the set \mathcal{A} . This is helpful in reducing computational time by avoiding integration over the entire domain boundary.

Chen et al. also promoted the use of an implicit analytical function, Φ , which required derivation of the geometric parameter relationship to primitives used in constructing the solid model. This representation changed the sensitivity outcome to

$$\frac{dF}{db} = \int_{\Omega(b)} \frac{\partial f}{\partial b} d\Omega + \int_{\partial\Omega(b)} \frac{f}{|\nabla \Phi|} \frac{\partial \Phi}{\partial b} d\Gamma. \tag{2.6}$$

An advantage of using this method is that an implicit representation is only required for primitives in the model and topology changes do not violate the calculation.

Armstrong et al. and Robinson et al. in [71, 72], respectively, followed a similar procedure as outlined by Choi and Kim and Chen et al. In contrast to the use of an implicit representation by Chen et al. Robinson et al. utilized finite-differencing of triangulation element centroids to find the design velocity of the entire domain boundary, as illustrated in Figure 2.3. This is akin to using finite-differencing of the triangulation nodes; however, issues with nodes found on intersecting faces are avoided by using element centroids. Armstrong et al. relied on the Boundary Method for Design Sensitivity (described in Choi and Kim [43]) by combining adjoint sensitivity maps with the design velocity field to calculate performance sensitivity in a single analysis.

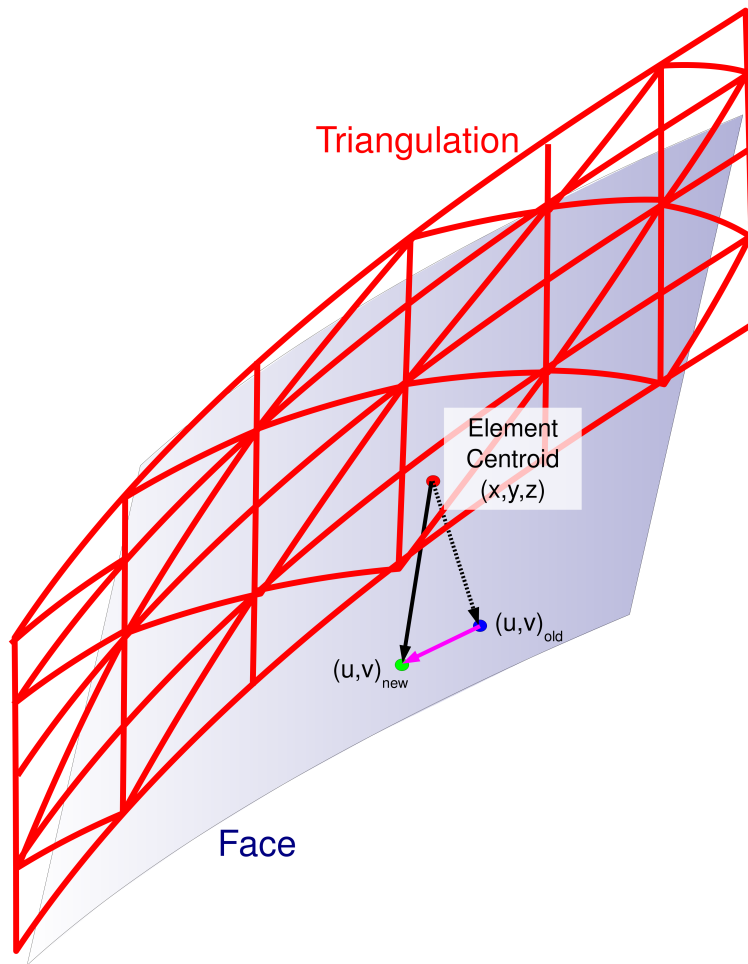


Figure 2.3: An illustration of the manner in which Robinson et al. [72] calculated the design velocity using the centroid of triangulation elements. Other researchers utilized the triangulation nodes instead of element centroids.

3 Open Conceptual Design Issues

After identifying the current state-of-the-art in conceptual design, two areas of growth are addressed in this section: conceptual design methodology, followed by CAD-based shape sensitivity analysis.

3.1 Conceptual Design Methodology

The current state of conceptual design methodology offers many opportunities for improvement. Low-fidelity tools utilizing empirical or statistical data for configuration sizing and performance prediction cannot be extrapolated for consideration of new, entirely different configuration concepts. Successful legacy codes are found to be inapplicable for new technology and new aircraft concepts as well, primarily due to a limited configuration parameter space describing an aircraft (e.g., legacy tube-and-wing designs), and thus eliminate exploration of a broader configuration design space that may contain better designs [54, 3]. Due to these tool limitations, the current methodology often delays discovery of configuration issues in new designs until much later in the design process; consequently, expensive engineering work-arounds and costly redesign are required to correct such issues [3, 11, 10].

It is also clear, though, that purely high-fidelity analysis in conceptual design would yield computationally expensive analysis of relatively few aircraft configurations. This scenario does not fit within the current, and future, scheduling constraints imposed on designers during conceptual design. A feasible compromise between low-fidelity and high-fidelity usage appears to be the appropriate direction of evolution for conceptual design methodologies [50]. This inherently brings forward the need for 3D models earlier in the design process.

In order to permit wider acceptance of high-fidelity analysis in conceptual design, a CAD-based methodology is required. CAD-free design methodologies provide much information about a design; however, translation of low-fidelity configuration parameters, or a topological FFD representation, into a CAD model becomes a necessity for implementation of later design phases. In essence, a methodological gap exists between the earliest geometric description of an aircraft and the later refined design that is realized prior to prototyping and manufacture [11]. Without ties to a feature-based 3D model, CAD-free geometry is not recreated exactly in a CAD system for later use. Some research publications, as in [5, 12], approximate the concept of CAD-based conceptual design by driving a CAD model with the perturbed dimensions an optimizer selects, yet the aerodynamics analysis depends on a separate, independently-generated mesh representation that is not derived from the 3D model. In such cases two geometric representations exist within the same framework: 1) an analytical mesh at the forefront of analysis and sensitivity calculations and 2) a CAD model serving as an in-series addition to display another version of the analytical mesh geometry (see Figure 2.1).

Furthermore, a methodology that approaches that of Knowledge Based engineering practices becomes a necessity. The current design-in-series methodology does not provide a solution to variances in the geometry representation throughout the design process. A centralized 3D model would provide consistent geometry representation between varying fidelity

codes. A robust methodology, or set of “best-practices,” for creating such a centralized 3D model are currently lacking.

Using the notion of a CAD-based centralized 3D model, for example, at the core of conceptual design underscores the need for careful “top-down” design of the CAD model feature tree. Current geometry libraries of aircraft configuration components may not exhibit the appropriate design intent. The multifidelity configuration parameter spaces need to drive the design intent of such components, in addition to engineering constraints; such a need, though, is specific to the analysis codes selected, each having different parameterizations of an aircraft configuration. As cited in [22], developing CAD-based 3D models with this methodology is not akin to traditional drafting. According to Carty et al. [54], understanding the CAD system strengths and weaknesses are paramount to ensure that such a model regenerates properly throughout a continuous set of driving dimensions; however, Bowcutt observes that reference datums sometimes do not permit all combinations of parameter dimensions (meaning the design space is not a hypercube) [10]. No general methods for a feature-tree recipe, or dimensioning of primitives, exist—each attempt is problem-specific.

Many of the researchers already cited agree that determining the optimal design vector of configuration parameters, instead of surface mesh nodes, results in reduced complexity for an optimizer. The latter undesired situation can be somewhat recreated in a CAD model if the design variables are set to be individual spline points, or control points. Many researchers have successfully used this method for two-dimensional airfoil analysis; however, the complexity of determining an optimal three-dimensional wing configuration, for example, may increase substantially as more splined airfoil sections are defined. Numerous local-minima may result since the tradeoff between perturbing one control point over another may not be easily distinguishable when, for instance, an objective function is calculating total drag.

In addition, the manner in which multiple internal aircraft subsystems are incorporated into a 3D model is not defined in the context of conceptual design. Zang et al. [50] identifies this need when both aerodynamic and structural high-fidelity analysis are desired. Without a 3D model created for multidisciplinary use, there is potential for loose coupling between the surface mesh and body mesh that requires many surface interface variables. This scenario may impact adjoint methods for sensitivity calculations. The other viable solution is to tightly couple the aerodynamic and structures codes, as done in ASWING; yet, Zang et al. report that typically only commercial codes (with no source code access) are available for structural analysis, thus making this option intractable.

Inclusion of a multidisciplinary 3D model opens new questions for conceptual design. The method in which multiple disciplines are included will determine the nature of the disciplinary results. For example, the underlying wing structure, usually designated by a wing box and wing ribs, can be constructed as a union of solid parts or as an assembly of solid parts. The FEA undertaken in both cases is very different. The assembly approach would permit greater flexibility for placement of structural components via careful use of mating constraints, while increasing the options for structural layout (such as total number of ribs, spar locations, etc.). Developing a methodology that can automatically construct

this scenario would require driving the design intent of the assembly, and individual solid parts, with the parameter space from multifidelity structural analysis codes.

3.2 CAD-based Shape Sensitivity Analysis

The work by Robinson et al. in [72] accomplished computation of the design velocity from a CAD model; yet, their approach required extensive computational time (more than the high-fidelity analysis portion of the optimization). Other issues were presented in their work, such as difficulty in dealing with topological changes (meaning extra faces were added or removed from the baseline 3D model after perturbation) when regenerating a perturbed solid model. Projection of triangulation element centroids onto a CAD face did not always land on the original face it was associated with, especially if topology changed. In some instances there was no topological change, yet face IDs changed due to the creation, or change, of slivers. It is hoped that a design velocity computation can occur with the projection of surface mesh element centroids, or even nodes, falling near the baseline projection after model perturbation. Some of the presented work-arounds to these issues in [72] were discussed as not being robust. Comparison of their method with a finite-difference sensitivity calculation yielded large discrepancy in results (factor of three) as well.

The CAD-based shape sensitivity work by Chen et al. [70] was limited by the need for an implicit representation to relate configuration parameters to primitives used in constructing the 3D model. It is expected that many complicated models will not have an obvious implicit representation of primitives defining the domain boundary. Other work relying on finite-differencing of tessellation nodes, such as that conducted by Jameson et al. [36] and Nemec et al. [66, 34, 35], are limited by the assumption that there be no topological change in the regenerated CAD model after perturbing a configuration parameter. If remeshing is instituted, then interpolation of the results between the two meshes is required since there is no guarantee that each tessellation node is retained. This increases computational time during each design cycle in order to handle the needs of retaining mesh history. Some methods exist to assist in these issues, as discussed in [73, 57, 74]. There is also a need to resolve the selection of step-sizes for the various geometric parameters being perturbed in finite-difference schemes; otherwise, as found in [67], inaccurate results do not result in optimizer convergence (especially for finite-difference errors greater than 1%) to true optima—more so for CFD calculations modeling flow regimes in transition or with turbulence. Lastly, it is unclear how to handle finite-differencing for nodes that are on the boundary of two faces.

4 Proposed Research

Three proposed research objectives are explained in this section with a general description of the approach needed to complete them. Each approach is meant to address some of the remaining open issues already discussed. Afterwards, the status of current work is given to provide a basis for the direction of future work.

4.1 Research Objectives

The improved design methodology presented in this work attempts to bridge the methodological gap between conceptual and preliminary design. In order to do so, multidisciplinary analysis must occur at various levels of fidelity during the conceptual design phase *as well as* across multiple design phases. Three major areas that contribute to this improved aircraft design methodology are shown in Figure 4.1. First, this improved methodology is facilitated with a compatible geometry representation, best obtained through a 3D model, that is both multidisciplinary and multifidelity. For example, a multidisciplinary CAD model geometry has multifidelity parameter spaces driving the design intent (i.e., the set of features created by geometrical operations and constrained primitives that result in a final solid model). The single 3D model thus becomes the aircraft representation for low-, medium- and high-fidelity parameter space for each analysis discipline.

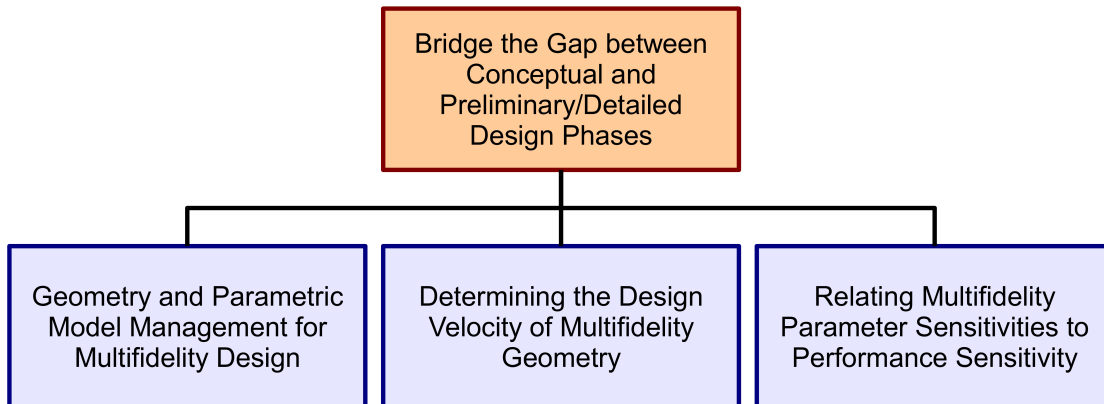


Figure 4.1: Research methodologies that will resolve the current gap found in aircraft design methodologies.

In addition, two other objectives are significant in enhancing the bridge across the methodological gap. In the case of gradient-based optimization, the calculation of the 3D model design velocity (i.e., the sensitivity of the 3D model topology to perturbations in the configuration parameters) needs development. Particularly robustness issues and computational time are matters of import in this work since multidisciplinary geometry is used with a multifidelity configuration space.

Lastly, the inclusion of multifidelity parameter sensitivities to the calculation of performance sensitivity requires development when applying gradient-based optimization. This

objective is essential to completely bridge the methodological gap. As the design path of steepest ascent follows gradient information in the design space, it must incorporate the effects of multifidelity configuration parameters. There are various ways to consider the change in multidisciplinary performance metrics over a multifidelity configuration space, such as applying a weighted combination, arithmetic mean or Taylor series expansion of the multifidelity sensitivities.

4.2 General Research Approach

4.2.1 Geometry and Parametric Model Management for Multifidelity Design

Achieving a multidisciplinary geometry with multifidelity configuration space is a major goal in this work. The technical approach for accomplishing this end involves identifying a set of best practices that engender a “top-down” design intent. This means that the sequence of geometric operations (i.e., a feature tree) that define the aircraft geometry are designed with a set of reference datums, geometric dimensions and constraints that ensure feasible relative design motion of primitives and components during regeneration.

Initially, the respective configuration parameter sets of select multifidelity codes are determined for multiple disciplines. The union of these parameter sets becomes the configuration space for the geometry. Some parameters may be dependent on others in the configuration space; others may be redundant. Secondly, after establishing the relationships, if any, between the parameters in the configuration space, a referencing system of datum planes and axes is derived that captures the design intent implied by each parameter. A multilevel design motion ensues as parameters are perturbed, where the relative motion of geometric entities occurs at the level of geometric primitives, sets of primitives (a component) and sets of components (an assembly) in the configuration. This is the embodiment of a “top-down” design intent. The set of best practices is reached when each level of fidelity in the geometry model is driven by the configuration space at different design times (i.e., one feasible design point to another), where every instance of regeneration occurs within a continuous parameter space between side bounds.

In addition to proper datum schemes, effectively constraining geometric primitives is equally important for the design intent to be complete. This also applies to mating constraints at the component and assembly level. Various constraint solutions are conceivable, for example, for internal structural components that ensure regeneration in concert with the outer mold lines; however, not all constraint schemes maintain the intended relative design motion when other parameters are modified. A study will ensue to determine the advantages and disadvantages of certain design practices using particular constraints.

Finally, the datums, geometric constraints and equation-driven model dimensions may influence regeneration time, an important consideration for an optimization framework. Knowledge gained from the work above may provide a better understanding of how to best minimize regeneration time as well. Regeneration time may be correlated to the level of complexity that datums and constraints add to solving the solid model equation set.

Other model robustness issues will also be addressed. For example, the intersection of a

wing upper and lower surface causes a failed regeneration. This depends on the airfoil definitions and spacing along the wing span, in addition to spline and lofting attributes. Model completeness will also be considered since 3D models require additional design parameters that are not part of the configuration parameter set of low-fidelity tools.

An attempt at quantifying the notion of “best practices” will be made based on how well this methodology can robustly regenerate throughout a feasible, continuous configuration space with minimal regeneration time. Based on these results, a degree of effectiveness will be attributed to the methodology presented herein. Such conclusions will relate the usefulness of this methodology in providing 3D geometry for multifidelity codes in multidisciplinary analysis.

4.2.2 Determining the Design Velocity of Multifidelity Geometry

The design velocity calculation is an important consideration when applying a 3D model that is both multidisciplinary and multifidelity to gradient-based optimization. As discussed previously, it is a crucial component to the calculation of performance sensitivities. This capability enhances the bridge across the current methodological gap in aircraft design. Not only can multidisciplinary analysis be conducted with multifidelity parameter spaces in conceptual design, but gradient-based optimization can be pursued also.

To accomplish this added capability, the active boundaries of the 3D model are identified for each parameter in the multidisciplinary, multifidelity configuration space. Only these boundaries impact the shape sensitivity analysis with a non-zero design velocity when a particular parameter is perturbed. Using this method, a dependancy graph will be created with this information. The capability also exists to create a dependancy graph relating a newly perturbed model topology to baseline topology, thus allowing the identification of active boundaries to occur with less computational time and greater robustness if topology changes.

The influence of the multifidelity configuration space is captured in design velocity fields. However, the high-fidelity configuration parameter sensitivities are only evident there. These sensitivity calculations rely on a tessellation of the 3D model surface or body (depending on the discipline of interest) and subsequent high-fidelity analysis of perturbed and baseline models. To properly accomplish this procedure, an improved method will be employed to ensure robust projection of tessellation elements (or nodes) onto the 3D model faces. This method will rely on the dependancy graphs discussed above and potentially result in lower computational time by eliminating incorrect projections. Ideally, this method will yield a consistent sensitivity calculation that is unhindered by a dependancy disconnect anywhere in the chain between configuration parameters, 3D model, active boundaries, tessellation geometry and topology variations.

4.2.3 Relating Multifidelity Parameter Sensitivities to Performance Sensitivity

By enhancing the bridge across the methodological gap with gradient-based optimization, a methodology must accompany that properly accounts for multifidelity sensitivity contri-

butions to overall performance sensitivities. An interesting aspect to this methodology is that the multifidelity configuration parameters may be entirely unrelated since they describe distinct geometric features of the aircraft (e.g., wing span may pertain to a low-fidelity set while the airfoil boattail angle pertains to a high-fidelity set). Here the high-fidelity set defines a separate collection of hyperplanes in the design space than the low-fidelity set and no physically-intuitive transformation exists between the two; yet, both can influence the same performance metric for the entire aircraft. This contrasts from multifidelity sets that may have a direct transformation from low- to high-fidelity space.

Initial studies will be conducted that consider various ways of including both low- and high-fidelity analysis results in the determination of a performance metric. These methods will guide how low- and high-fidelity sensitivities are formulated to impact a performance sensitivity as well. Weighted linear combinations, such as averaging, and Taylor series expansions are two possible methods of formulating the relationship between a performance metric and both low- and high-fidelity calculations of that metric. Details for these developments are preliminary and, although not presented here, will continue to mature. Other methods will also be investigated in conjunction with the two mentioned above. This work will result in a methodology that enables combining the low- and high-fidelity calculations of performance metrics and sensitivities (in multiple disciplines) for gradient-based optimization.

4.3 Summary of Current Work

Work has commenced in creating a multidisciplinary 3D model with multifidelity configuration parameter space. The configuration parameters come from select codes introduced previously: PASS, ASWING and Cart3D. PASS provides a modular framework wherein other disciplinary analysis codes can be integrated using the Java Native Interface (JNI). It also provides mission performance calculations for an entire configuration and includes an internal optimizer (simplex or GA). ASWING is a medium-fidelity code that couples aerodynamic and structures formulation. The location of structural components, as well as cross-section properties (including mass, inertia, stiffness, etc.), are required to conduct analysis. Until a high-fidelity structures code, such as NASTRAN, is implemented, ASWING provides the structural analysis in the framework. PASS also contains the analysis of other disciplines, such as a weight estimate and stability characteristics, using empirical formulations.

Figure 4.2 depicts a simplified schematic of the eventual design framework that will be used to test the methodologies proposed herein. PASS will by-pass its own aerodynamics and structures formulations to call Cart3D, or NASTRAN (not shown), using a model management decision criterion yet developed. An option to call ASWING is provided for a medium-fidelity aerodynamic and structural response as well. A web-services approach, with XML data transfer, will be implemented; until then, file IO is the current *modus operandi* between PASS and other modules. ASWING is currently not integrated with PASS. CAPRI codes have been developed to tessellate a SolidWorks solid model for use in Cart3D.

Table 4.1 provides a comparison of the variable length parameter spaces found in the multifidelity codes selected above. The parameter set for ASWING varies depending on how

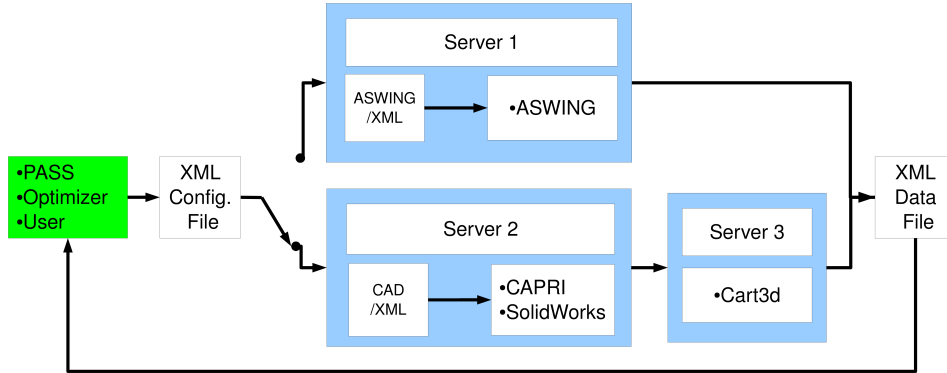


Figure 4.2: A simple schematic of the proposed multifidelity MDO framework that will serve as a testbed for the methodologies proposed herein.

	PASS (low-fidelity)	ASWING (medium-fidelity)	Cart3D (high-fidelity)
Wing	20	$41N_s + 2N_f$	
Empennage	13	$2(41N_s + 2N_f)$	$\mathcal{O}(10^5)$ to $\mathcal{O}(10^6)$
Fuselage	16	$41N_s$	
Propulsion	$7 + 3N_e$	$13N_e$	

Table 4.1: A comparison of the variable length parameter spaces found in the geometric representation of an aircraft by PASS and ASWING. The third column refers to an estimate of the number of degrees of freedom possible with Cart3D. The notation is defined as: $N_e \equiv \#$ of engines, $N_s \equiv \#$ of span-wise stations and $N_f \equiv \#$ of flap span-wise stations.

much configuration data is available *a priori*. The parameter set in the low- and medium-fidelity design space become the driving geometric parameters for the centralized CAD model. A triangulation, originating from the CAD model surface, is essentially a set of nodal degrees of freedom. In contrast to the case of FFD methods, for example, where the surface mesh itself is the geometric representation undergoing optimization via nodal or control point perturbations, the degrees of freedom in the surface triangulation are not used as design variables.

By combining the parameter space in the low- and medium-fidelity codes for the wing, for example, a 3D model was created as seen in Figure 4.3. Similar work was done for empennage and fuselage bodies. A trial-and-error process was used to determine an adequate design intent, including placement of datum references, primitive constraints and primitive dimensioning, for the wing and fuselage bodies. An example of a resulting aircraft configuration is seen in Figure 4.4, where each variable fidelity code obtains information from the CAD model (via CAPRI). An optimizer is expected to provide new design vector feedback to the CAD model for regeneration after making sensitivity, objective function and constraint evaluations. This solid model thus becomes a type of data repository for the multifidelity

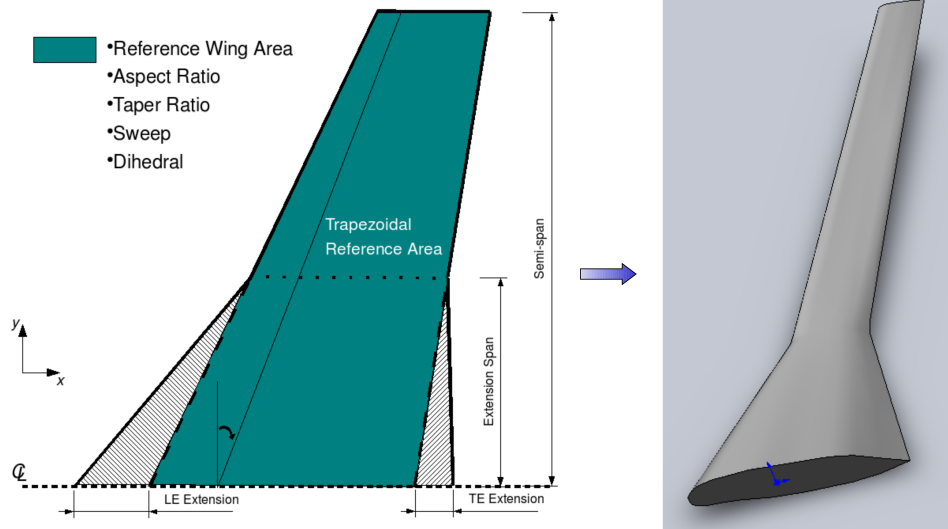


Figure 4.3: A depiction of a wing planform layout, as defined by low- and medium-fidelity configuration parameters, providing the design intent for a wing solid model.

parameter space of each analysis code.

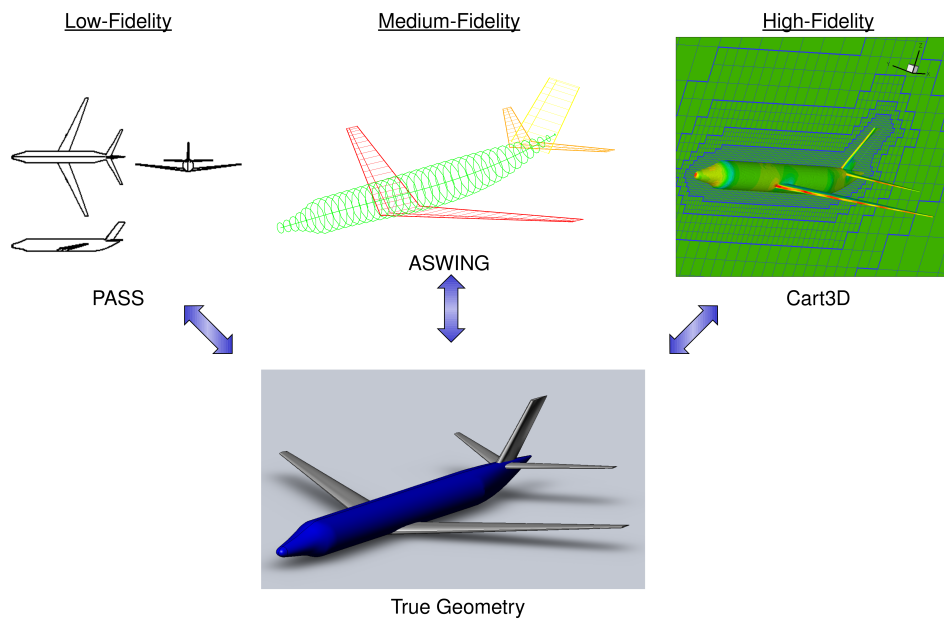


Figure 4.4: The concept of a centralized CAD solid model, as shown here, feeds-forward parameter information for disciplinary analysis codes and receives a new design vector as feedback from an optimizer for regeneration.

5 Expected Contributions

In consideration of the proposed work previously outlined, the following contributions to the fields of conceptual aircraft design are expected:

1. A consistent geometry representation for all design phases;
2. Viability of high-fidelity analysis in conceptual design;
3. A methodology for parameterizing 3D models with an appropriate design intent;
4. A 3D model representation that is both multifidelity and multidisciplinary (e.g., outer mold lines with internal structural layout);
5. An increased awareness of configuration-level design flaws that leads to earlier, potentially less-costly remedies;
6. A potentially larger design space can be probed with improved confidence in performance results due to the inclusion of high-fidelity analysis;
7. Configuration changes, or down-select, rely on high-fidelity analysis results;
8. Subsequent design phases may add or suppress 3D model features to a centralized and consistent 3D geometry;
9. Application of gradient-based optimization with multifidelity analysis using a single 3D model;
10. More robust and computationally efficient method for determining the design velocity of a 3D model;
11. Appropriate accounting of multifidelity configuration parameter sensitivities for performance sensitivity calculations.

6 Research Timeline

The following table contains a proposed timeline for completion of various research phases associated with this proposal:

Phase Duration	Task
Nov08 – Jan09	<ul style="list-style-type: none"> • Undertake methodology development of multidisciplinary 3D models with multifidelity configuration parameter spaces • Conduct feasibility, robustness and “best-practices” studies • Develop multidisciplinary, multifidelity 3D model geometry examples
Feb09 – Apr09	<ul style="list-style-type: none"> • Develop the design velocity calculation methodology • Using the 3D model geometry already developed, test robustness and computational efficiency with usage of dependancy graphs
May09 – Jul09	<ul style="list-style-type: none"> • Investigate various methodologies for properly including multifidelity paramater sensitivities in the calculation of multidisciplinary performance sensitivities • Utilize 3D models and design velocity methods from the previous research phases
Aug09 – Dec09	<ul style="list-style-type: none"> • Complete a multifidelity MDO design framework to experiment with the coupling of the various methodologies above in a conceptual design setting • Resolve issues with the framework integration • Demonstrate the feasibility and effectiveness of the improved conceptual design methodology
Jan10 – Mar10	<ul style="list-style-type: none"> • Write Thesis Draft
Apr10 – May10	<ul style="list-style-type: none"> • Finish Thesis • Thesis Defense

Table 6.1: Anticipated research project timeline.

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