

## **Rotorcraft Conceptual Design Environment**

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### **Abstract**

Requirements for a rotorcraft conceptual design environment are discussed, from the perspective of a government laboratory. Rotorcraft design work in a government laboratory must support research, by producing technology impact assessments and defining the context for research and development; and must support the acquisition process, including capability assessments and quantitative evaluation of designs, concepts, and alternatives. An information manager that will enable increased fidelity of analysis early in the design effort is described. This manager will be a framework to organize information that describes the aircraft, and enable movement of that information to and from analyses. Finally, a recently developed rotorcraft system analysis tool is described.

### **Introduction**

This paper considers the environment for effective execution of conceptual design of advanced rotorcraft. Requirements for such an environment are discussed from the perspective of a government laboratory that is conducting research and supporting rotorcraft acquisition. To some extent the perspective is even narrower, considering specifically the authors' laboratories (NASA and AFDD at Ames Research Center in the United States).

The objectives of rotorcraft design work in a government laboratory are to support research and to support rotorcraft acquisition. Research activities require robust design capability to aid in technology impact assessments and to provide system level context for research. At the applied research level, it is necessary to show how technology will impact future systems, and justify the levels of investment required to mature that technology to an engineering development state of readiness. Design provides one avenue to accomplishing that objective. The acquisition phases requiring rotorcraft design work include concept exploration, concept decision, concept refinement, and technology development. During these

acquisition phases, it is typically necessary to evaluate a wide array of rotorcraft concepts, and independently synthesize new concepts; to conduct capability assessments, in order to provide the foundation for specifications and requirements; and to perform quantitative evaluation of aircraft designs, design concepts, and design alternatives.

The initial stages of the aircraft design process are described as conceptual design and preliminary design, consisting of imaginative and creative derivation and optimization of the overall system such that the design meets the requirements within the constraints. The conceptual design and preliminary design steps are each supported by analysis and model test. Each step is carried to sufficient substantiation and detail to provide credibility and show the promise that will enable the process to continue to the next stage.

### **Design Context**

The steps in aircraft design have been long recognized<sup>[1,2,3]</sup>, but the role of design in a government laboratory is different from that in the rest of the community. In industry, design is directed towards a product, with many people involved. In academia, work aimed at a graduate degree necessarily involves primarily a single person, with a focus on one dimension of the complex tasks (frequently MDAO today). In a research laboratory, the focus is more on analysis than on design. In a government laboratory design work is required to support research and acquisition as described above, generally with separate design and analysis objectives. Even so, design in a

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government laboratory should be conducted as if directed towards a product so the results are credible and well support the objectives. Government laboratories in the U.S. do not build aircraft, so the design work stops short of a product. The designs are not intended to move forward in the development process, rather provide reference points for requirements development and technology impact assessment. One consequence of this role of design in a government laboratory is that we need not be concerned with the precise definition of conceptual design and preliminary design.

Rotorcraft conceptual design in a government laboratory consists of analysis, synthesis, and optimization to find the best aircraft meeting the required capabilities and performance. A conceptual design tool is used for synthesis (design) and analysis of rotorcraft. This tool historically has been low fidelity for rapid application. Such a sizing code is built around the use of momentum theory for rotors, classical finite wing theory, a referred parameter engine model, and semi-empirical weight estimation techniques. The successful use of a low-fidelity tool requires careful consideration of model input parameters and judicious comparison with existing aircraft to avoid unjustified extrapolation of results.

### **Model Fidelity**

Meeting the objectives of conceptual design in a government laboratory depends on the correctness of the design decisions, which depends on the accuracy of the information, requiring a high-fidelity analysis capability. In this context, fidelity means accuracy. Issues regarding the level of physics, the correctness of the equations, the extent of approximations, the resolution of matter and motion are implications of fidelity. Demonstration of accuracy (which is not the subject of this paper) is based on comparison with test data. A model is higher fidelity than another model only if the uncertainty of the former is less than that of the latter. A model is the high (or highest) fidelity if its uncertainty is within the error bound of the experimental data, so its results are indistinguishable from the performance of the actual physical realization. The current state-of-the-art is that improvements of accuracy are still required in all disciplines.

Improving design decisions requires increasing the fidelity of analysis early in the design process. High-fidelity analysis is required because of the increasing sophistication of requirements and technology, demanding an increased level of certainty for critical performance parameters, in order to distinguish between system concepts and enable informed decisions. As we expect greater performance out of rotorcraft, write more intelligent specifications, and differentiate between a wider array of viable concepts,

the requirement for higher fidelity analysis becomes increasingly important.

Typically in current practice, high-fidelity analysis does not replace low fidelity in sizing tasks, but rather supports development and calibration of low-fidelity models. It is possible now to utilize the best, most powerful analyses in conceptual design<sup>[4]</sup>, but the process is slow and tortured, preventing effective early use of high-fidelity analysis. The increased utilization of higher fidelity analysis is enabled by high performance computing assets. Execution time of the analysis and availability of computational resources remain factors of course. Execution time is always improving, but tools of varying levels of fidelity are still required. A key obstacle in bringing high-fidelity analysis to the conceptual design process is the bottlenecks introduced as information is exchanged between analyses.

### **Information Manager**

Figure 1 shows the current information flow of the typical rotorcraft design process in our laboratories. Each tool must communicate with all other tools (often with manual transfer of data), which requires multiple, separate interfaces. A consequence of this approach is quadratic growth in interfaces as the number of tools increases. Note that the conceptual design tool is not the center of the process. The figure indicates the important higher fidelity tools, in areas of rotorcraft comprehensive analyses (for performance and loads), rotor and airframe structural design (for weight), computational fluid dynamics (for performance), and flight dynamics simulation (for handling qualities). This architecture is a source of significant inefficiency. The emphasis on information flow in this discussion reflects the state of environment development in our laboratories.

The design environment requires an information manager, as illustrated in Figure 2. The information manager is a framework to organize the information that describes the aircraft, and enable movement of that information to and from analysis tools. This will be a collaborative environment with a unified rotorcraft description, permitting effective access to multi-fidelity analyses. Each tool communicates only with the information manager, so for each tool only a single interface is required, with automated push/pull of data. Note that the conceptual design tool is still not the center of the process. The information manager includes a geometry engine, with an interface to the grid/mesh tools needed for aerodynamic and structural analysis.

Eventually the information manager might become an execution manager as well. Also, some analysis functions may migrate to the framework, such as global optimization and development of surrogate models. It will be necessary to wrap or package tools and processes, so they can operate with the framework.

An execution manager must also deal with distributed computation requirements.

The environment will manage fidelity by managing information flow among tools, with the resulting efficiency enabling early application of high-fidelity analysis. The framework must be so useable and so productive that it draws in legacy codes, including rotorcraft comprehensive analyses.

The tasks are collaborative, as ultimately all design work must be. The information manager facilitates collaboration, by bringing to the environment central data, standard interfaces and methods, and independence from serial flow of information. The information manager must implement design version control. There is of course still a need for a chief designer.

The application of high-fidelity analysis early in the design process depends on high performance, integrated distributed computation. Yet different uses imply different levels of access to computing resources. There is thus a need for stand-alone, laptop implementation of the environment, expandable with wireless access.

### **Geometry Engine**

The geometry engine in the information manager implements a central description of the rotorcraft: geometry, attributes, features, properties, and topology. To facilitate design changes, the aircraft description must be a flexible, modular, parametric, and hierarchical. There must be context-specific views of the data, and each tool requires a tailored level of detail. There will be geometry conventions at the system level. Effective, useable grid/mesh tools are essential for productivity. The environment must accommodate multiple grid/mesh tools, for both aerodynamic and structural analyses.

In an industry environment, the information must ultimately support manufacturing, so at some point in the design process the geometry information moves to a CAD system, for an exact, detailed representation of the system. CAD has a solid model representation, which is also required for some high-fidelity analyses. The challenge is to make the transition to CAD at the correct point in the process, since thereafter maintaining consistency of geometry representation between the geometry engine, the grid/mesh tools, and CAD is difficult. Changes made in the grid/mesh tools must flow back to CAD, and changes in CAD must flow back to the central description. The conceptual design environment will not drive the choice of the CAD system, hence must accommodate the CAD systems in use.

A government laboratory does not support manufacturing, so moving the model to CAD need not be considered. Indeed a high end CAD system has

more functionality than needed for conceptual design in a government laboratory.

A consistent multi-fidelity geometry description is needed in order to support a hierarchy of analysis fidelity<sup>[5]</sup>. This will be a subset of CAD functionality, based on parameterized geometry and component aggregation<sup>[6]</sup>. One approach is to start with simple geometry models for low-fidelity analyses, and introduce progressive refinement and elaboration of the geometry representation as required for the analysis level involved. The geometry engine will drive grid/mesh generation. Thus modifications of geometry are developed in the engine, not in the grid/mesh tools. Otherwise developing and maintaining the capability to get geometry modifications from all grid/mesh tools back to the geometry engine would be necessary. Layout and visualization capability will be functions of the geometry engine, information might still be sent to the CAD system for layout. An alternative approach would be to build the geometry engine on an existing CAD system (one that has parametrization of geometry), developing hierarchical representations, aggregation, and simplification for low fidelity. However, this approach would require access to the CAD code, and would tie the geometry engine to the CAD system selected.

### **Optimization**

The design process involves local optimization, including the sizing iteration and structural design (typically to minimize weight given loads) of components. The environment must also accommodate system optimization (global MDAO). System optimization might be implemented with surrogate models (response surface methodology, or metamodels) to represent higher fidelity results efficiently in synthesis. In the context of the design environment, optimization is just another information flow, another process.

A particular challenge for optimization in the context of conceptual design within a government laboratory is the definition of the relevant objective function that captures the diverse set of requirements typical of modern multirole rotorcraft.

### **Hierarchy Of Fidelity**

High-fidelity analysis replaces low-fidelity analysis as a design evolves. The design and optimization processes should identify when higher fidelity is needed. Typically the design space is explored with low-fidelity tools, then local optimization is performed using high-fidelity tools. High-fidelity analysis is also used to calibrate low-fidelity tools (another information flow, another process). Thus variable fidelity is required, tailored for an efficient process.

High-fidelity analysis requires a high-fidelity description of system, adding design fidelity to go with the increased analysis fidelity. For example, there will be a difference between the simple representation for visualization and layout work in support of conceptual design, and the geometric detail needed to produce accurate outer-mold-line description for CFD analysis of performance. The introduction of additional design tasks is characteristic of the use of higher-fidelity analysis in conceptual design, and is a challenge to improving the processes.

What is required is right-fidelity analysis, not simply high-fidelity. There may be little value and unacceptable costs associated with defining conceptual designs to a level of detail greater than needed to differentiate between them, or needed to assess technical risk and payoff. The driving choice in analysis fidelity is not the highest fidelity that can be computationally afforded, but rather the minimum level of fidelity needed to reach an acceptable level of uncertainty. Right-fidelity is likely to vary across disciplines, but care must be exercised and tools created to ensure that model consistency is maintained regardless of the fidelity utilized. It is desirable to use low-fidelity (inexpensive) analyses as much as possible, with occasional recourse to higher fidelity (more computationally demanding) analyses<sup>[7]</sup>.

Initially the engineer must decide what constitutes right-fidelity, based on experience and results of dedicated analyses. Eventually the conceptual design framework should guide and assist in the choices. Thus the information manager must take on significant tasks, in order to intelligently maintain data on capabilities and uncertainties of analysis tools, based on experience and correlation, and to determine when improvements in the fidelity of tools are required. The information manager must recognize the need for higher-fidelity analysis, and define the level of analysis fidelity needed, based on propagation of uncertainty in the design process and system and subsystem objective functions. Hence the information manager will know what constitutes right-fidelity, based on the current status of the design. Trust-region model-management approaches provide a way to combine models of different fidelity<sup>[7,8]</sup>, using quantitative assessment of low-fidelity model predictive capability to impose limits on optimization performed with that model and decide when to invoke high-fidelity analyses. Adaptively building low-fidelity models from sampled high-fidelity data is also possible, with the high-fidelity evaluations selected based on a balance of expected system performance and uncertainty estimates.

### **Design Environment**

Although this paper discusses some unique aspects of the conceptual design environment, much effort has been expended on the subject. A number of key

investigations are cited here. There has been work on the issues of rapid conceptual design<sup>[9]</sup>, covering tools to facilitate integrated design analysis and optimization, with the objective of reducing the cycle time associated with performing multidisciplinary design, analysis, and optimization. Many projects are dealing with multi-fidelity geometry definition, to support hierarchy of design fidelity during conceptual and preliminary design phases<sup>[5]</sup> and parametric representation of wing and body geometry<sup>[6]</sup>. An interesting application of a collaborative design framework<sup>[10]</sup> used Intelligent Master Modeling (IMM) technology (which provided a “master” representation that captures product, engineering knowledge, and design and analysis process from preliminary design to detailed analysis), CAD Interoperability (provided a framework and standards for geometry creation and manipulation independent of CAD systems), and Federated Intelligent Product Environment technology (provided a distributed environment for process integration and engineering computation).

An example of a framework specific to rotorcraft is the Rotorcraft Conceptual Design and Analysis (RCDA)<sup>[11]</sup>. This tool suite, integrated in an environment based on ModelCenter®, includes sizing codes, optimizers, and geometry conventions. This work with RCDA emphasizes the complexity of choices and high degree of interdependency among attributes and subsystems in modern design that makes MDAO (multidisciplinary analysis and optimization) a key enabler to success in the conceptual design phase, and the work illustrates the significant benefits that are accrued from extending this capability into the early stages of preliminary design. The constraint — and challenge — is to embed MDAO and sufficiently accurate analyses into the development process without an adverse impact to program development cost and time, ultimately achieving reduced cost and time as well as a more optimized product. MDAO is more efficient with simple models of conceptual design, and becomes increasingly expensive with the move to higher-fidelity tools in preliminary design. Consequently this work<sup>[11]</sup> emphasized improvements in efficiency with automation within the integrated design environment.

There are ongoing programs that are expected to begin to address the requirements identified here. Notable is the CREATE program (Computational Research and Engineering for Acquisition Tools and Environments)<sup>[12]</sup>, which has the goal of improving the efficiency of U.S. DoD acquisition engineering by inserting computationally based engineering tools throughout the acquisition process. The CREATE program will develop next-generation computational solvers and optimizers and insert more multi-physics-based analysis earlier in the design cycle. The Air Vehicles component CREATE-AV<sup>[13]</sup> includes a rotating wing analysis project (Helios)<sup>[14]</sup> and a conceptual design project (DaVinci)<sup>[15,16]</sup>. The

CREATE-AV/CD DaVinci Project has the mission of enhancing the DoD acquisition process by providing multi-disciplinary, multi-fidelity, computationally-based systems engineering design tool sets. The DaVinci Project vision is to develop software architecture and tools specifically for acquisition system engineering design, analysis, and optimization; and develop and transition maintainable, extensible, validated, scalable, and useable computationally based engineering tools. The highest priority of the project is rapid parametric system modeling, utilizing libraries of pre-engineered components and associated analysis tools in a unified system engineering framework. In addition, the CREATE-MG Magic project<sup>[12]</sup> deals with geometry and meshing (both generation and manipulation) for the aerodynamic and structural analysis.

### **Conceptual Design Tool**

Next we consider the status of conceptual design tools in our laboratories, in particular tools for synthesis (design) and analysis of rotorcraft. Such tools utilize low-fidelity models for rapid application. The helicopter industry has proprietary tools, including PRESTO (Bell Helicopter), RDM (Sikorsky Aircraft), and HESCOMP and VASCOMP (Boeing). Until now the tools available to the U.S. government have been characterized by out-of-date technology and software, and limited capabilities. Examples are HESCOMP and VASCOMP (developed by Boeing in the 1970's), and RC (developed by the U.S. Army AFDD in the 1990's).

NASA, with support from the U.S. Army, conducted in 2005 the NASA Heavy Lift Rotorcraft Systems Investigation<sup>[17]</sup>, focused on the design and in-depth analysis of rotorcraft configurations that could satisfy the Vehicle Systems Program (VSP) technology goals. The VSP technology goals and mission were intended to identify enabling technology for civil application of heavy lift rotorcraft. The goals emphasized efficient cruise and hover, efficient structure, low noise. The requirements included carrying 120 passengers over a 1200 nm range, 350 knots at 30,000 ft altitude. The configurations considered included the Large Civil Tiltrotor (LCTR), Large Civil Tandem Compound (LCTC), and Large Advancing Blade Concept (LABC). This project is an example of the role of a rotorcraft sizing code within a government laboratory. The design tool used was the AFDD RC code. The project illustrated the difficulties adapting or modifying a legacy code for configurations other than conventional helicopter and tiltrotor. Thus requirements were developed for a new conceptual design tool.

The principal tasks of a sizing code are to design (size) rotorcraft to meet specified requirements, including vertical takeoff and landing (VTOL) operation, and to analyze the performance of aircraft for a set of flight

conditions and missions. The code must consider multiple, flexible design requirements for sizing, from specific flight conditions and various missions. The aircraft performance analysis must cover the entire spectrum of aircraft capabilities. The component performance and engine models must cover all operating conditions. These capabilities require a general and flexible definition of conditions and missions. For government applications and research support, the code must model general rotorcraft configurations, estimate performance and weights of advanced rotor concepts, and model the impact of new technology at both system and component levels. Software extensions and modifications are expected to be routinely required in order to meet the unique aspects of individual projects. The architecture must accommodate configuration flexibility and alternate models, including a hierarchy of model fidelity, even though the code is initially implemented with low-fidelity models typical of the conceptual design environment. The architecture must allow multidisciplinary design and analysis. The software design should facilitate extensions and modifications. Complete and thorough documentation of both the theory and the code is essential, to support development and maintenance and to enable effective use and modification.

### **NDARC**

Based on the above requirements, a new rotorcraft system analysis tool has been developed to support future needs of the NASA Subsonic Rotary Wing project and the AFDD Advanced Design Office: NDARC — NASA Design and Analysis of Rotorcraft<sup>[18]</sup>. NDARC has a similar level of fidelity as legacy codes, specifically built around the use of momentum theory for rotors, classical finite wing theory, a referred parameter engine model, and semi-empirical weight estimation techniques. NDARC is however built on a new framework designed for flexibility and modularity, hence with the ability to rapidly model a wide array of rotorcraft concepts. Critical to achieving this capability is decomposition of the aircraft system into a set of fundamental components, which can then be assembled to form wide variety of configurations.

The tasks performed by NDARC are outlined in Figure 3. A job consists of one or more cases, each case optionally performing design and analysis tasks. The design task sizes a rotorcraft to satisfy specified design conditions and missions. The analysis tasks include off-design mission performance analysis and calculation of flight performance for point operating conditions. A aircraft description for an analysis task can come from the sizing task, from a previous case or previous NDARC job, or be independently generated (such as a description of an existing aircraft). The code can generate performance maps of airframe aerodynamics or engine performance. The description

and analysis of conventional rotorcraft configurations is facilitated, including single main rotor and tail rotor helicopter, tandem rotor helicopter, coaxial rotor helicopter, and tiltrotor configurations (Figure 4). Novel and advanced concepts are typically modeled by starting with one of these conventional configurations. For example, a compound rotorcraft can be constructed by adding wings and propellers to a rotorcraft.

#### *Missions and Flight Conditions*

Missions are defined for the sizing task and for mission analysis. Each mission consists of number of mission segments. For each segment the time, distance, and fuel burn are evaluated. Mission parameters include mission takeoff gross weight and useful load. Takeoff gross weight can be input, fallout, or maximized (for power required equal power available). With a specified takeoff fuel weight the mission time or distance can be adjusted so the fuel required for the mission (burned plus reserve) equals the takeoff fuel weight. The mission iteration is on time or distance (if adjustable), or on fuel weight.

Flight conditions are specified for the sizing task and for flight performance analysis. Flight condition parameters include gross weight and useful load. Gross weight can be input, fallout, or maximized (for power required equal power available).

A flight state is defined for each mission segment and each flight condition. Aircraft performance is analyzed for a specified state, or for maximum effort performance. Maximum effort is specified by a quantity (such as best endurance or best range, or power required equal power available) and a variable (such as speed, rate of climb, or altitude). The aircraft must be trimmed in the specified operating condition, solving for controls and motion that produce aircraft force and moment equilibrium (and/or designated quantities equal a target value). Various flight states can require different trim strategies. The solution of blade flap equations of motion may be required, in order to evaluate rotor inplane forces or blade pitch angles.

#### *Aircraft Description*

The aircraft consists of a set of components, including fuselage, landing gear, fuel tank, rotors, forces, wing, tails, and propulsion groups. A rotor is designated a main rotor, tail rotor, or propeller; and can be tilting, ducted, and/or anti-torque. Twin rotors can be considered in the performance calculation. The force component implements a simple weight and fuel flow description. A propulsion group is a set of rotors and engine groups, connected by a drive system. Each engine group has one or more engines of the same type. Components define the power required, and engine groups define the power available. Weights are calculated or input for all components and subsystems.

Aerodynamic loads (especially drag) are calculated for all components.

The ability to define the aircraft control structure through input is a key feature for configuration generality. Aircraft controls are connected to component controls. Aircraft controls consist of pilot's controls (for trim), configuration variables (e.g. tilt of nacelle/pylon, engine, rotor shaft), and direct connections to component controls. There can be one or more control states, with different connections to components (for example, to model the controls of a tiltrotor in helicopter mode and airplane mode flight). There are default control connections for each configuration.

The rotor power required is evaluated using the energy method, as a sum of induced, profile, and parasite power. The power components are calculated in terms of an induced power factor and a mean drag coefficient, including induced power for twin rotors.

A propulsion group is a set of rotors and engine groups, connected by a drive system. There are one or more drive states, with a set of gear ratios for each state. The power required equals the sum of component power, transmission losses, and accessory losses. There are drive system torque limits, and rotor and engine shaft ratings. Each engine group has one or more engines of the same type. The engine performance information includes mass flow, fuel flow, jet thrust, and momentum drag at the required power. A Referred Parameter Turbohaft Engine Model enables the aircraft performance analysis to cover entire spectrum of operation. This model uses curve fits of referred performance from an engine deck, including the effect of turbine speed. The effects of size (scaling model, based on mass flow) and technology (specific power and specific fuel consumption) are included in the engine model.

#### *NDARC Development Cases*

The NDARC development test cases include the UH-60A helicopter, CH-47D tandem, XH-59A coaxial, and XV-15 tiltrotor (Figure 4). These cases were selected because for each aircraft there are available flight performance data, weight statements, geometry, and a comprehensive analysis model. Validation and verification of performance, weights, and engines were conducted for fixed aircraft, then the capability to size aircraft was explored with these models.

#### **Concluding Remarks**

A vision of a rotorcraft conceptual design environment for government laboratories has been described. A key requirement is to increase the fidelity of analysis early in the design effort, which will be enabled by an information manager in the environment. The manager must be a framework to organize information that describes the aircraft, and enable movement of that

information to and from analyses. The result will be a collaborative design environment, with a unified rotorcraft description, permitting effective access to multi-fidelity analyses.

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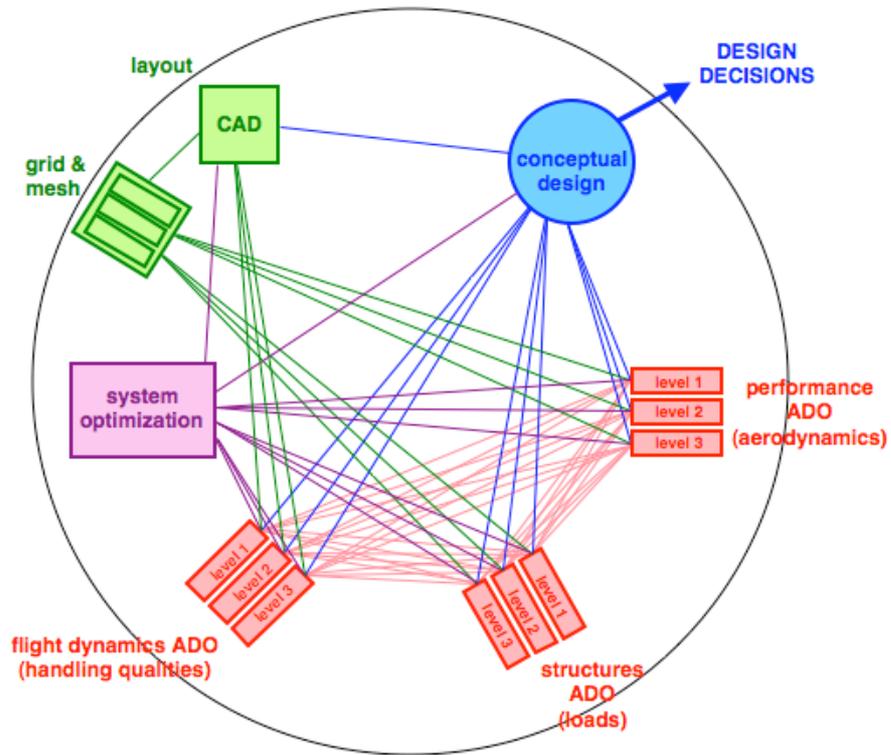


Figure 1: Current information flow in conceptual design (ADO is analysis, design, and optimization).

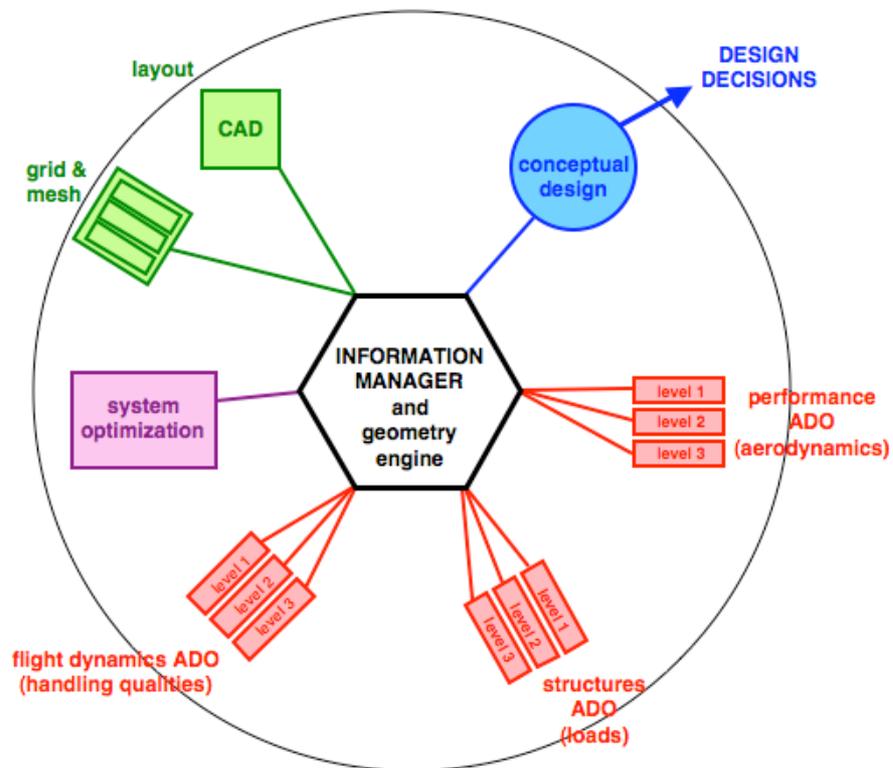


Figure 2: Conceptual design environment with an information manager.

