JOURNAL OF AIRCRAFT
Vol. 47, No. 5, September–October 2010

Design Forum

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Designing for a Green Future: A Unified Aircraft Design Methodology

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DOI: 10.2514/1.C000239

Aristotle once said "the whole is more than the sum of its parts." It is in Aristotle's words that a basis for a greener aviation industry can be found. By looking at the whole, the aerospace community can make the entire air transportation system sustainable for generations to come. The effect of aviation on the environment is a multifaceted problem with far reaching consequences if addressed improperly. For this reason, the proposed methodology provides a strategic planning capability for environmental technologies. This unified methodology is a top-down-bottom-up approach starting and ending with the air transportation system, and is intended to align technology selection with an organization's long term environmental concerns. The objective is to systematically identify technologies worth investment based on their environmental impact throughout the future air transportation system. This unified methodology for green design provides the fundamental framework to make purposeful technology selections and investment decisions to meet the environmental needs of the future.

I. Introduction

THROUGHOUT history, humans have strived to climb the highest peaks, build the tallest buildings, and soar through the skies. However, in our careless pursuit of these aspirations, we have caused what could be irreversible damage to our planet. This vicissitude, however, slow or minute it may appear, will drastically alter the way we live our lives.

Although the aviation industry produces only 3% of all man-made emissions,** there are still significant concerns about its environmental impact. The demand for aviation is growing†† and due to its particularly damaging high-altitude emissions‡‡ the ramifications of increased demand could be catastrophic. However, there is still hope. To alleviate this environmental burden and provide for a sustainable future, organizations must transform the way they operate. With the industry's abounding size, even small improvements can have a far reaching effect. With the potential to improve aviation, the world's most respected agencies, companies, and universities are dedicated to finding sustainable solutions to slow degeneration and maybe even someday restore balance to the environment.

Society's heightened environmental awareness has spawned the development of copious new requirements, procedural modifications, concepts, and technologies, all under the auspicious *green* classification. This push raises two important questions: what exactly does the concept of green entail, and how are green concepts best implemented for a sustainable future?

We do not inherit the earth from our ancestors; we borrow it from our children. (Native American Proverb)

II. Defining Green

The research conducted for this unified methodology uncovered a plethora of definitions for green. Despite the abundance of definitions, not a single definition incorporated all the essential aspects of economic and environmental responsibility. Many definitions related the concept erroneously to human health and not to the health of the planet, while each ignored the implications of a company's economic sustainability by becoming green. For this reason, the authors created a definition for green that would incorporate all the attributes of an environmentally conscious company. *Green: Accommodating expeditious and continual environmental and economic sustainability.*

Although short spoken, this definition requires a great depth of knowledge to quantify the environmental and economic impacts throughout the complete life cycle of an organization's practices and products. For large complicated systems, such as the air

Received 29 December 2009; revision received 11 June 2010; accepted for publication 21 June 2010.

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**Data available online at http://www.iata.org/whatwedo/environment/climate_change.htm [retrieved 16 March 2009].

††Data available online at http://www.foe.co.uk/resource/reports/aviation_tyndall_summary.pdf [retrieved 16 March 2009].

‡‡Data available online at http://www.guardian.co.uk/environment/2009/jan/16/plane-emissions-heathrow-third-runway [retrieved 6 March 2009].

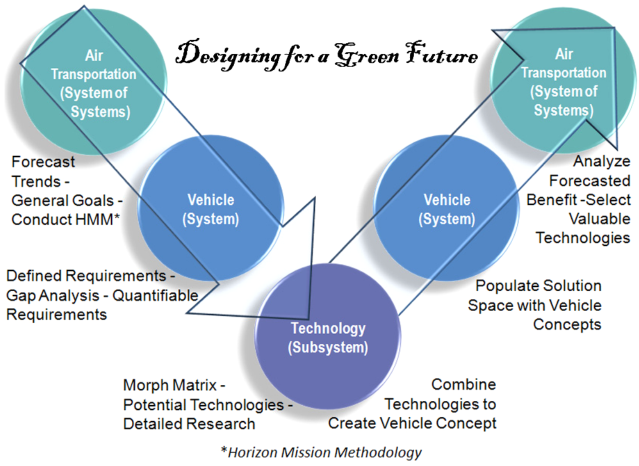

Fig. 1 Design methodology.

transportation industry, this means companies must consider not only the life cycle of their technologies, but also the integrated system and its interactions with other systems. The ultimate objective is to start reducing a company's environmental footprint today, and ensure it will continue to be reduced tomorrow.

III. Objective

As the aviation industry continues to shift to an environmentally focused design paradigm, a large number of technologies that promise to reduce emissions are being proposed by industry and academia. While each technology provides hope for significant improvements individually, their interactions must be understood to create a greener air transportation system and not just a greener vehicle. To address these interactions, a methodology to be implemented later with a company's specific capabilities is proposed to provide a strategic planning process cultivating environmental technologies. The remainder of this paper describes the unified methodology, which is illustrated through a case study of the U.S. market. It is important to keep in mind that the case study is just an example of how this methodology is implemented, and can be adapted to analyze a problem on any scale.

IV. Design Methodology

The methodology, illustrated as a V-diagram in Fig. 1, is a top-down-bottom-up approach that starts and ends with the air transportation system. The objective of this methodology is to identify technologies worth investment based on their potential environmental impact throughout the air transportation system. It decomposes the problem with specific environmental objectives, then generates and evaluates potential solutions to address how a company can achieve its overarching goals.

Following Fig. 1, it can be seen that at the air transportation level the methodology uses preliminary goals to assess potential areas for environmental improvement. These goals may be qualitative, such as a desire to reduce fuel consumption, or quantitative, like the reduction of CO_2 emissions by 50% per passenger kilometer. They are used to identify which areas of the fleet, such as aircraft passenger capacity, will provide the largest environmental improvement to the air transportation system as a whole.

As the process flows down to the vehicle level, the areas identified from the air transportation system analysis are used to further define requirements. Once requirements are quantifiably defined, a vehicle level gap analysis is performed to determine if evolutionary or revolutionary changes are necessary to meet the company's environmental goals.

The air transportation and vehicle system information then disseminates further down to the subsystem level where a matrix of alternatives is populated with technology concepts. These technology alternatives are researched for their life-cycle impact on closing the previously identified gaps. On the way back up the V-diagram, vehicle concepts are then synthesized by combining various technologies from the matrix to be once again analyzed in the air transportation system. The technologies yielding the most overall environmental benefit are identified, and a cost to benefit ratio determined. By tracking the cost to benefit ratio, designers can assure alignment of their long term green goals, while simultaneously maintaining affordable air travel and the company's overall sustainability. The following discussion steps through the diagram above in detail to explain data collection, analysis, and evaluation.

A. Air Transportation Forecasting

The overall flow for this segment is depicted in Fig. 2 where the light boxes with sharp edges represent processes which manipulate data, while the tangible results are represented by dark boxes with rounded edges. This subprocess begins with the development of scenarios for the future of aviation, including time frame, growth, and network structures, ultimately terminating with the identification of areas of improvement to be passed down to later subprocesses.

1. Trend Forecasting

Driving this subprocess are top level goals identified from a company's future vision, secondary stakeholders in the air transportation

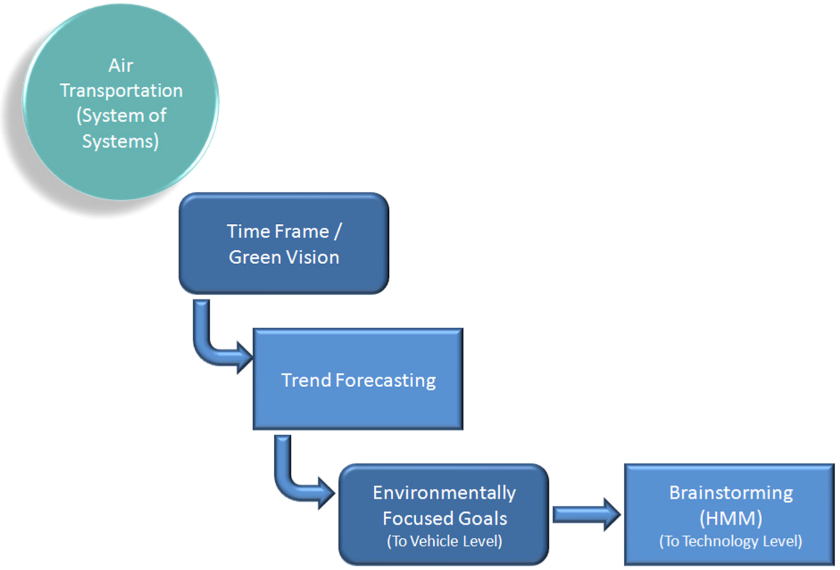

Fig. 2 Fleet level flow down of proposed method.

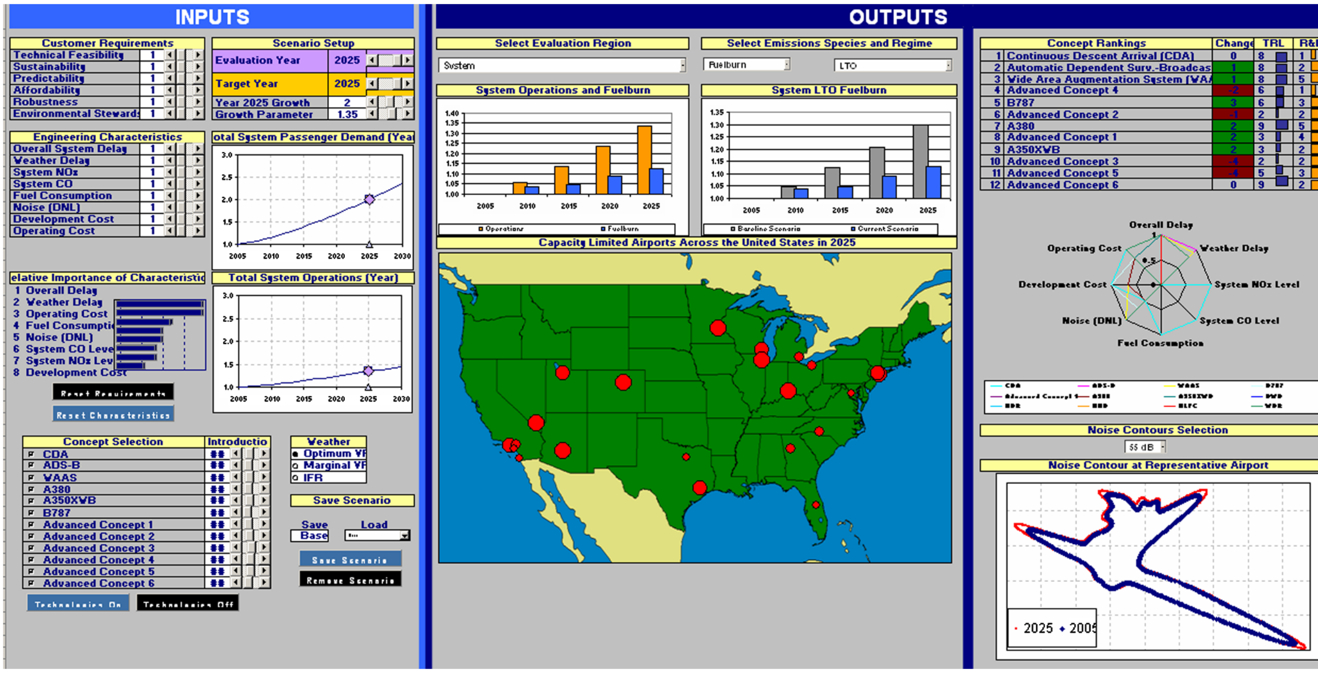

Fig. 3 Requirements identification environment.

system, and the expected growth in demand for air travel. To gain an understanding of these goals and how they drive future technology development, an analysis tool is implemented to assess the relative magnitude of influence of technologies and concepts on the air transportation system.

For this case study, a tool incorporating over 135 U.S. airports, handling 97% of U.S. air transportation was created and can be seen in Fig. 3. For a more global implementation of the methodology, European, U.S., and other international data should be used to develop a similar analysis tool to identify the influence of the global fleet on the air transportation system.

The example analysis tool provided here uses advanced design techniques to generate parametric surrogate models representing the air transportation system, aircraft emissions, scheduling impacts of increased demand, and the introduction of new technologies and aircraft. The 2005 Campbell–Hill database of detailed worldwide aircraft information, as well as respected U.S. codes, AEDT (Aviation Environment Design Tool, by the FAA and NASA) and MEANS (MIT Extensible Air Network Simulation) are used to develop the neural network surrogate equations that provide all background calculations. By making this analysis environment parametric with surrogate models, rapid analyses can be performed to examine a number of different future goals and growth scenarios. Varying stakeholder requirements, scenarios, and technology settings allows potential environmental improvements to be defined and long term technology requirements determined. (More information on this analysis environment can be found in [1].)

For the U.S. case study, this analysis shows that a seat class of 100–200 passengers has a significant impact on the aviation system. Because of the already existing large market and expected increases in demand, even moderate improvements on vehicles in this class will create significant environmental benefits in the overall air transportation system. Additionally, results from this analysis identify technological areas which have a considerable environmental impact. As an example technological area important in the U.S., alternative fuels will be investigated later in this paper.

2. *Horizon Mission Methodology*

To prevent the premature over development of requirements, and to infuse creativity into the process, a variation of the Horizon Mission Methodology (HMM) [2] is used. This structured brainstorming session draws on the insight provided by the air transportation system analysis to pose several futuristic scenarios to a forum. The scenarios are designed to be achievable in the time span desired, and they place the audience at the end of the time span to compel them to look back on the changes that have occurred. The discussion and results of these scenarios are then analyzed for similarities, ultimately identifying necessary qualitative gaps to be closed, as well as creative solutions to meet future needs.

For this study, the implementation of the HMM forum consisted of 25 Ph.D. Doctoral candidates, and Master's students. In this instance, some participants were chosen outside the field of aerospace engineering to increase the diversity of the forum. When combining the results from all of the scenarios, trends begin to appear. For instance, the overcrowding of large hubs will drive aircraft to carry hub infrastructure enabling them to use general aviation airports. To account for this, means of loading passengers on and off the aircraft will drive loading ramps and passenger stored luggage racks. Additionally, this will require security systems integrated into the aircraft structure directly, such as air-condition systems that can detect malice material carried onboard. These creative solutions are later used to populate a matrix of alternatives, and are then further investigated for their life-cycle impacts on the air transportation system and the environment.

B. Vehicle Analysis

The next step is to quantify the qualitative information considered so far. This process requires enumerating environmental goals from earlier analyses so the feasibility of meeting the overarching objectives can be systematically analyzed. The steps progressing through extracting requirements and the gap analysis are illustrated in Fig. 4. As can be seen, this next subprocess begins with extracting quantitative requirements, and leads to the identification of physical gaps between current aircraft configurations and the environmentally focused requirements.

1. *Identify and Extract Requirements*

The first step of the vehicle analysis is to combine the information developed from the air transportation forecasting and requirements from other company sources. These additional company requirements may come from marketing departments, operations analysis departments, or other industry analyses. The sources of these requirements for this case study are U.S. and international agencies, which dictate environmental and operational objectives such as

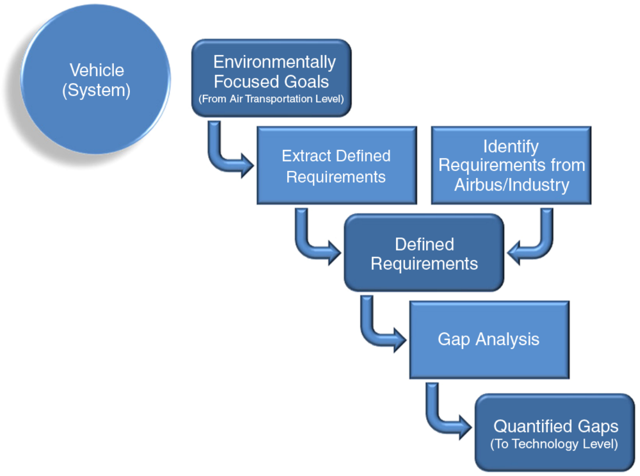

Fig. 4 Vehicle level flow down of proposed method.

NASA's $N + 2$ goals. Some of the key requirements to be modeled from these sources include a reduction of fuel weight by 15%, a 70% reduction in NOx, and reducing takeoff and landing field lengths to less than 3000 ft [3,4]. Because the air transportation system analysis identified that a medium seat class aircraft will have a significant impact on the aviation system in the U.S., the payload weight for an A320 is chosen to conduct a vehicle gap analysis.

2. *Gap Analysis*

Once all requirements are quantifiably defined, it is necessary to identify the gap between where the company currently is and where the company wants to be. For this U.S. case study, NASA's Flight Optimization System (FLOPS) is employed using a notional A320 aircraft. The results of the baseline aircraft and corresponding gaps are presented in Table 1.

To aid in the visualization of these gaps, a traditional wing loading versus thrust loading plot is provided in Fig. 5, with each point representing a different technology infused notional A320 design point. The following figure shows the design space and the physical gap from current configurations to meet the environmental targets identified above. Correlations indicate that the success of a conventional tube and wing design is highly dependent on the feasibility of achieving low weight, and high lift characteristics. From this study, an A320 class vehicle would require reducing the wing loading by half and nearly doubling the thrust to weight ratio. As a result of these requirements, this gap analysis shows the need to move toward more revolutionary concepts since meeting the needs of the future is well outside the capabilities of conventional tube and wing designs. However, if it could be shown that conventional aircraft configurations come close to fulfilling environmental constraints, this method for a gap analysis also provides insight into the areas of interest for further study.

C. Subsystem Analysis

With the physical gaps quantified and insight gathered from the HMM forum, the next subprocess can begin. At this subsystem level, information from previous subprocesses is used to populate a morphological matrix of alternatives, ultimately leading to the

Table 1 Quantified gaps (values in table are approximations from a notional A320 model with a designed range of 3000 nm and 150 passengers)

	LdgFL , ft	TOFL, ft	Fuel wt, lb	NOx, lb
Target	3000	3000	−15%	−70%
A320 Baseline	6547	6835	50,488	572
Gaps	3547	3835	7573	400

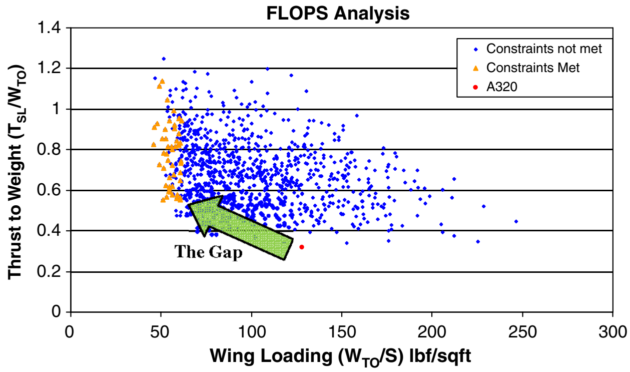

Fig. 5 A320 gap analysis (feasible points require double the thrust and a third the fuel consumption without incurring penalties in weight or structure).

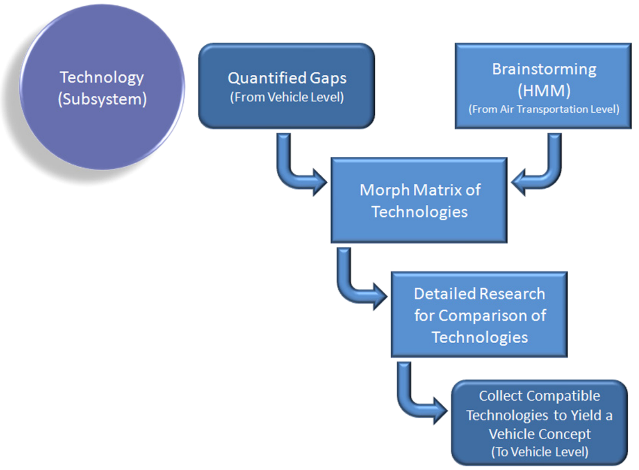

Fig. 6 Technology level flow down of proposed method.

collection of compatible technologies to yield vehicle concepts. The framework for this subsystem analysis is seen in Fig. 6.

1. *Morphological Matrix of Alternatives*

To aid in the subsystem technology analysis, a systematic tool known as a morphological matrix of alternatives is employed. This matrix of alternatives provides an extensive list of possible choices for the synthesis of an aircraft. This subprocess uses the insight gained from the gap analysis and focuses on expanding the creative concepts developed by the HMM session. At this level, it is important to expand the solution space without restriction to find different combinations of technologies and concepts which will sufficiently improve future vehicle systems.

Creating the matrix begins with the functional and physical breakdown of the aircraft. Attributes such as fuselage configuration, wing shape, high lift devices, engine selection, and manufacturing methods create the framework for the morphological matrix as seen in Fig. 7.

After the physical and functional decomposition is complete, possible solutions to fulfill each attribute category are determined using ideas developed through the HMM forum and additional research. As an example, possible wing structures can include internally braced, strut braced, truss braced, cable, and others. This process continues for each attribute category until all conceivable concepts have been exhausted. After the matrix is populated, the selection of a single concept from each category is used to represent the conceptual synthesis of an aircraft.

If the matrix is sufficiently large, as it was for this trade study with over 11 quintillion combinations, several techniques should be employed to reduce the solution space. One of the approaches used in this study is the interaction/compatibility matrix. The compatibility

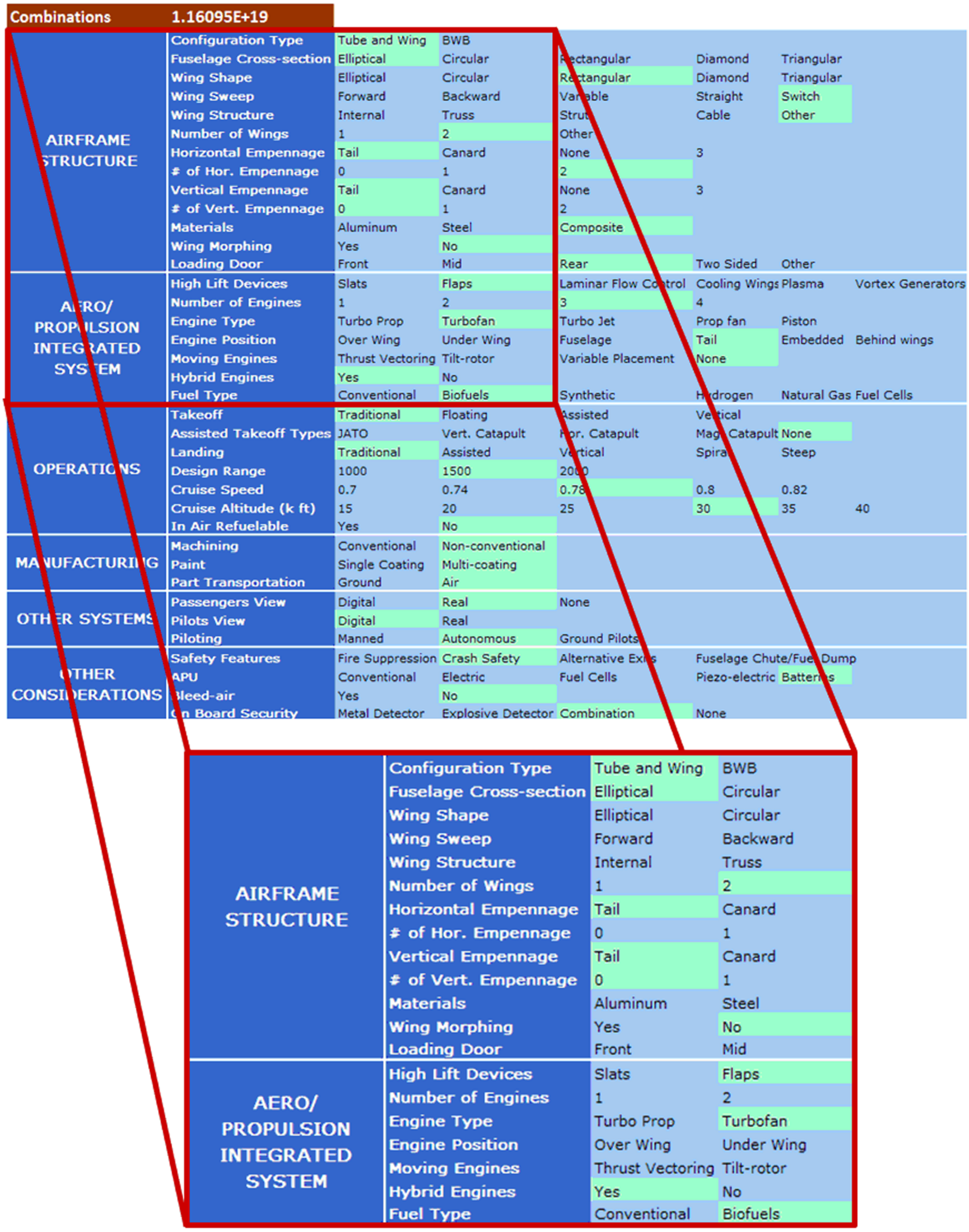

Fig. 7 Example morphological matrix of alternatives (lighter shading identifies selected items).

matrix reduces the solution space by removing technologies which do not work together or are redundant. As an example, a blended wing body concept cannot have a cable supported wing, and thus these choices are incompatible and cannot be selected together.

An additional approach to reduce the solution space is the use of positive compatibility. This concept is similar to the compatibility matrix aforementioned, but instead identifies technologies which interact favorably with one another, focusing design efforts in the development of system level concepts.

2. *Detailed Subsystem Research: Alternative Fuels*

With the morphological matrix developed, and groups of compatible technologies determined, further reduction of the solution space is completed by life-cycle analyses. To narrow the selection of solutions to those which provide the largest environmental impact, key attributes are investigated and additional trade studies are conducted at a subsystem level. It is important to note that this is implemented as a down selection method, and life-cycle analyses should still be performed on the integrated system. As an example for this case study, an alternative fuel trade study is performed. It is important to keep in mind that many other detailed subsystem analyses may be conducted based on the scope of the project and the needs of the company. To demonstrate the type of data to be collected and analyzed, a tool has been created for this study, the Alternative Fuels Life-cycle Model (AFLiM), and is described below.

The objective of creating AFLiM is to develop a comprehensive well-to-wake model representing the life cycle[§§] of possible alternative fuels for the U.S. case study. It is imperative to analyze each fuel throughout its life cycle to understand its true viability and

[§§]Data available online at http://www.caafi.org/information/pdf/CAAFI_factsheet_21oct08.pdf [retrieved 2008].

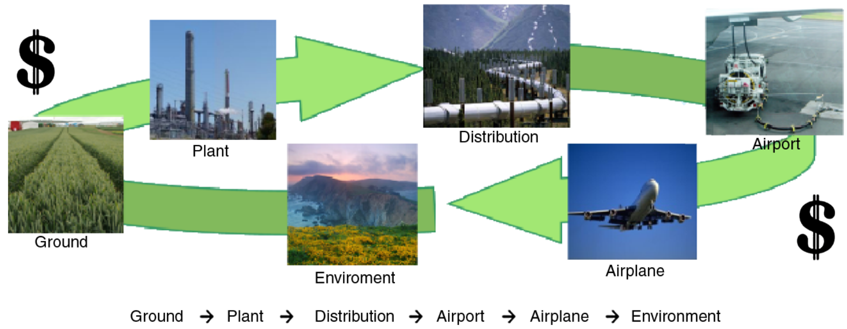

Fig. 8 Life-cycle representation for alternative fuels 0.

impact on the environment. The life cycle for this subsystem is broken down into three primary areas: production, distribution, and use. A visual representation is provided in Fig. 8.

The plethora of alternative fuel options available requires initial criteria to be determined so choices outside of the desired framework of the problem can be eliminated. Because the time frame for this example case study is the next 20 years, a drop-in fuel (fuels that can be used in the current infrastructure with little to no modification) is the primary selection criteria and is evaluated using metrics defining each fuel's compatibility with existing infrastructure. The evaluation of drop-in fuel is conducted based on performance of these metrics through a multi-attribute decision making process known as TOPSIS (Technique for Ordered Preference by Similarity to Ideal Solution) [5]. This results in the further analysis of algae, coal, natural gas, and soy as feedstocks through two refining processes, transesterification and Fischer-Tropsch. These fuels are defined through metrics representing characteristics desired in a fuel. The metrics for this study include energy efficiency, sustainability, capital and recurring cost, maturity of technology, energy independence, safety, and environmental impact. After extensive research, a score is given to each fuel for each metric. These metrics can then also be used to drive subcontractor requirements in the development of the fuel to assure streamline integration with top level goals.

To account for different future circumstances, variable weightings are applied to each of the metrics before evaluating the fuels. These weightings are determined based on each metric's relative importance in a possible future scenario. Below, the interface for the dynamic environment AFLiM is provided as seen in Fig. 9. The user inputs are identified by parts A, C, and D while the outputs of the tool are in B, E, and F. The radargram is used to identify areas where the subsystem is underperforming.

In light of the uncertainty associated with predicting future world conditions, a Monte Carlo simulation is performed on the relative importance of each alternative fuel metric. This process reveals the sensitivity of each fuel to the prescribed weightings. Since one set of weightings only represents the importance of each metric in one future scenario, varying the weightings and running numerous cases allows the fuels that are robust in many different scenarios to be identified, enabling the selection of the best alternative fuel in terms of robust performance.

The results of the Monte Carlo simulation show that fuels made from algae through either the Fischer–Tropsch or the trans-esterification process are the most robust solutions for the U.S. This identifies algae is one of the most promising choices in the fuel subcategory of the morphological matrix.

D. Concept Synthesis

With the top-down decomposition complete, the bottom-up recomposition through vehicle synthesis and evaluation can begin. Once sufficient information is gathered on each subsystem through life-cycle analyses, various combinations of technologies and

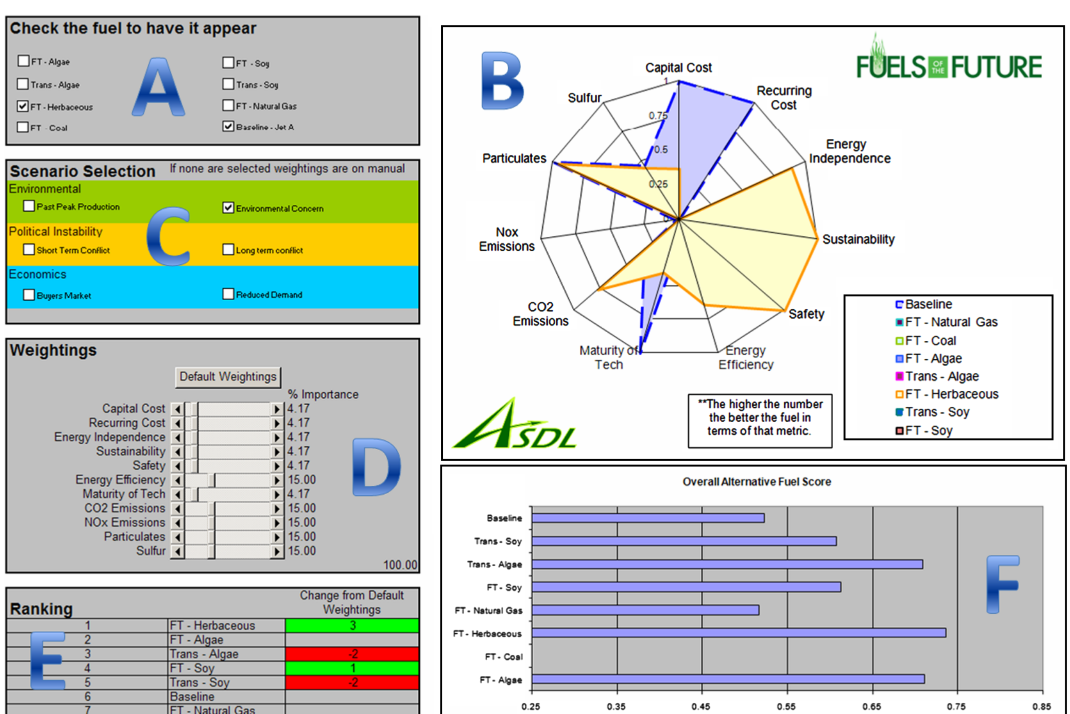

Fig. 9 Alternative fuels tool.

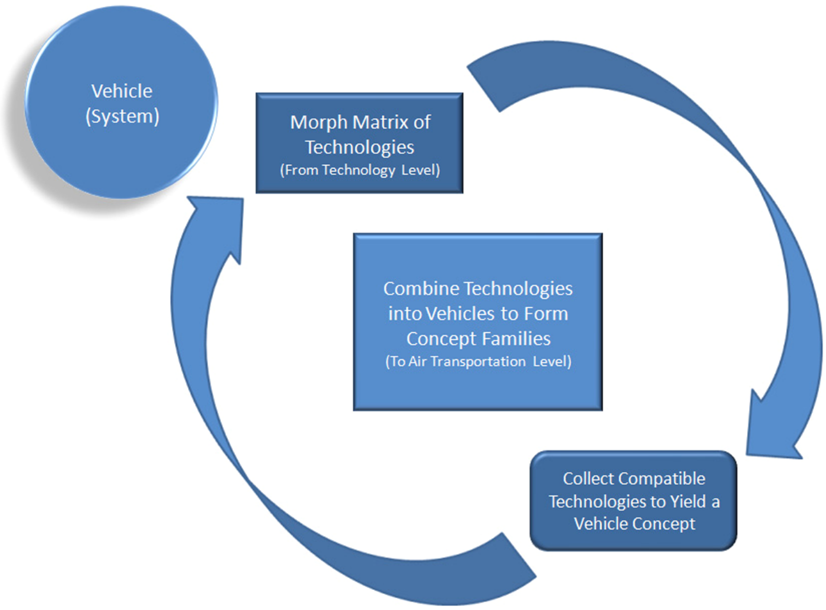

Fig. 10 Vehicle level flow up of proposed method.

configurations can be used to synthesize a vehicle concept using the morphological matrix. The repetition of this process is indicated in Fig. 10.

As an example of this process, one conceptual configuration created for this case study used alternative fuel from algae, electric fan thrust augmentation, and assorted other technologies to yield a vehicle similar to that illustrated in Fig. 11 ([6,7]). This collection of technologies and the resulting configuration is one example of the many concepts and technology bundles to be created at this step. Each concept is created by selecting various combinations of technologies in the morphological matrix, and should have emphasis on robust technologies identified through the life-cycle analyses. To observe the true effect of this vehicle on the air transportation system, its environmental impact must be propagated throughout the fleet.

At this stage, it is crucial to select enough concepts with various combinations of technologies, to assure the solution space is well represented for final evaluation in the air transportation system. In some analysis methods, this process can be automated to produce a large number of technology infused configurations, as can be seen in Fig. 12. When the process is automated, a visual down selection should be performed to select the concepts which have merit based on expert judgment.

Through successive iterations of the matrix of alternatives, a large number of aircraft to be propagated back through the air transportation system can be identified. Technology combinations can be implemented on an array of vehicles to provide insight regarding the benefit of specific technologies on the overall air transportation system.

E. Propagation of Vehicles through the Air Transportation Industry

Finally, vehicle concepts are integrated back into the air transportation system. Estimations are developed relating the effect of each technology on performance metrics of the configurations, and are then used to develop surrogate equations to be implemented in the air transportation evaluation tool. These estimations can be determined in a number of ways depending on required fidelity. Techniques such as polling experts or running computer simulations can provide the information for assessing the overall impact. As can be seen in Fig. 13 this final stage begins with conceptual configurations from the morphological matrix, and finalizes with the identification of promising technologies worthy of long term investment.

During this final subprocess, instead of evaluating and selecting notional vehicles, conceptual configurations are compared against each other along with nonaircraft technologies, such as advanced air traffic management concepts like Continuous Decent Arrivals. By modeling and evaluating these aircraft and nonaircraft concepts together in a single tool (Fig. 3), useful insight is gained regarding the utility of a configuration and its interaction with other air traffic management concepts. Finally, the top scoring concepts are ranked

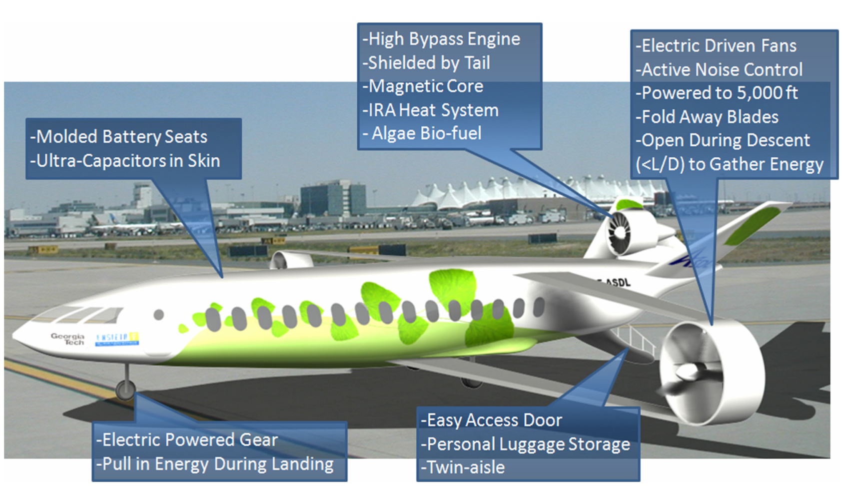

Fig. 11 Example concept from example case study (rendition created from [7] by Alexis Brugère, Georgia Tech).

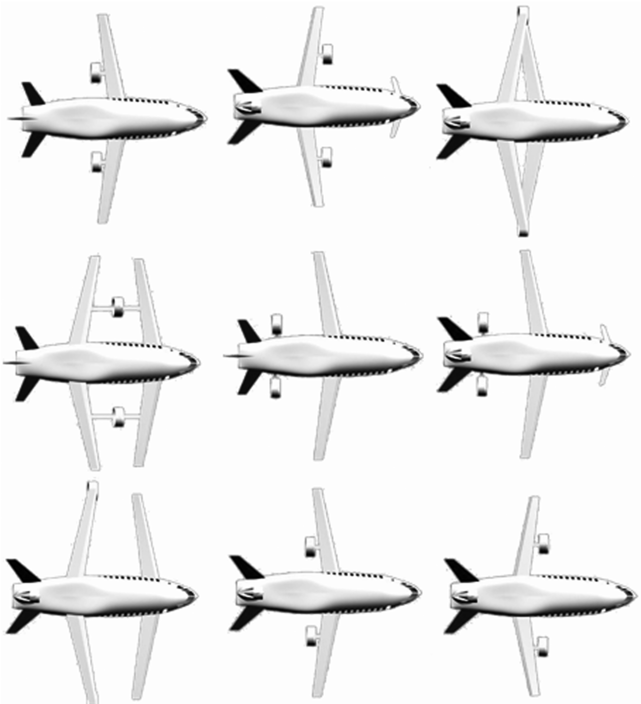

Fig. 12 Example technology infused configurations.

Ranking	Concept	Ultra High Bypass Engines	Electric Propulsion	Chevrons	Active Noise Control	Laminar Flow Control	Magnetic Core	Transesterification Algae Fuel	IRA Heat System	Moldable Lithium Polymer Batteries
1	Advanced Concept 2	+		+		+	+	+		
4	Advanced Concept 4		+		+	+				+
5	B787									
6	Advanced Concept 6		+		+		+			+
7	A380									
8	Advanced Concept 1	+		+					+	
9	A350XWB									
10	Advanced Concept 3	+	+					+		+
11	Advanced Concept 5		+		+	+				+
	Totals	3	4	2	3	3	2	2	1	4

Fig. 14 Decomposed concept technologies.

and decomposed into technology sets as seen in Fig. 14. Over each scenario assessed and all concepts investigated, the technologies which appear most frequently are combined to create the most robust set of technologies.

For this elementary example, coreless brushless motors and moldable lithium polymer batteries show the greatest environmental performance gains over all other technologies. In addition, laminar flow control and active noise control appear frequently among top ranking concepts. As a result, further investment in these areas will likely provide the most benefit for meeting the stipulated environmental goals set in the time frame specified. Using this information and the cost identified in the life-cycle analysis, the technologies with the best cost to benefit ratio can be determined. It should be stressed here that these results are merely an example technology set to be determined, and further repeatable analysis should be performed to confirm these results.

V. Conclusions

As shown throughout this study, designing for a green future in aviation depends on the ability of engineers to fully investigate both concept aircraft and their impact on the air transportation system. The process outlined here provides a methodology for the development of future aircraft through the identification of promising technologies worthy of investment to meet future environmental goals.

The main framework, starting with eco-efficient goals down through technology identification and back up through the air transportation system analysis has been developed. This methodology is adaptable to current analysis techniques and capabilities, potential technologies, other geographical markets of interest, and specific goals pertinent to current Aerospace companies. The true beauty of this methodology is its ability to be adapted to the needs and available information of a company. For aircraft manufactures like Boeing and Airbus, it could be beneficial to expand the focus to a global scale. In doing so, it will be crucial for the design team conducting the study to fully define the resources and infrastructure in the differing regions of operation. For example, many different alternative fuels can be produced more readily in different regions of the world. As a result, one focus of an international aircraft manufacturer may involve working closely with various subcontractors for the design of a truly robust engine which could use a wide variety of fuel

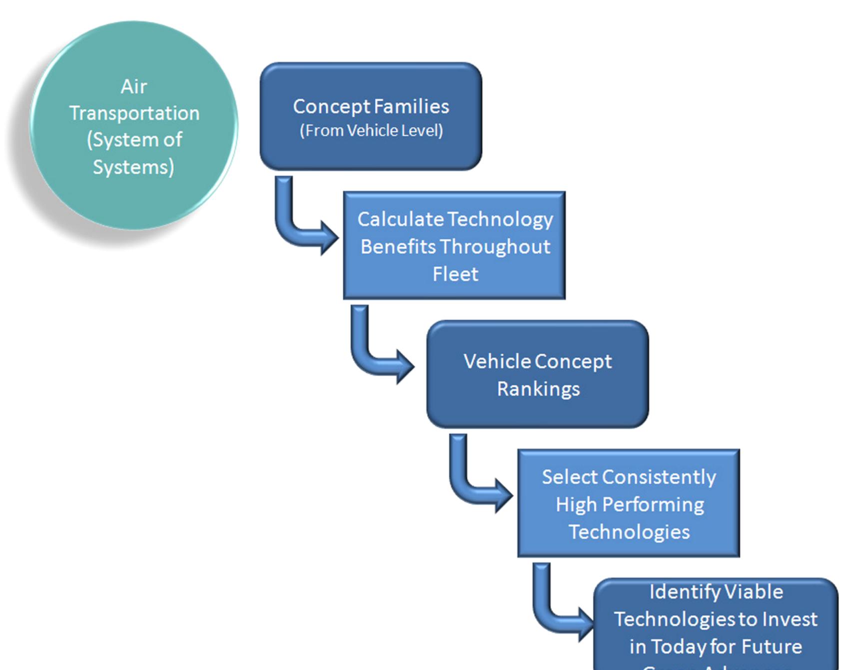

Fig. 13 Fleet level technology selection of proposed method.

types. By doing this, the company's sustainability can be addressed while also reducing the global environmental impact of their product.

Ultimately, if the aviation industry is truly dedicated to providing for a sustainable and more environmentally friendly future, every aspect of the market needs to be scrutinized. There must be a scientific and verifiable approach to technology development, because only purposeful decisions will lead to the improvements necessary for the continued success and expansion of the aviation industry.

Acknowledgments

Special thanks to Alexis Brugère, Kevin Johnson, Graham Burdette, Alexandre Bellaicco, and Mathieu Lanusse.

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