APPLICATIONS OF GAME THEORY IN A SYSTEMS DESIGN APPROACH TO STRATEGIC ENGINE SELECTION

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Abstract

Engine development programs present difficult and complex problems for manufacturers. The technical requirements have historically been addressed through performance analyses using "physics-based" codes. To assess economic viability of the engine programs, firms typically carry out extensive market and financial analyses. However, these analyses typically fail to consider competitive market uncertainties due to limited information about the competitor and the market. The use of game theory is explored in this paper as a method to assist the selection process of commercial engine architectures in the presence of competitive uncertainties. A strategic simulation model is developed that represents the decision analysis for a particular engine company. Information is continuously fed back from the market (and competitors) in order to allow the designer to identify the most profitable and competitive engines. Game theory-enabled analysis integrated into this simulation within the strategic decision model provides a basis for a systematic exploration of both engineering and business decisions. The analysis employs game theories to enumerate the decisions, moves, available and to formulate a process by which a winning decision can be achieved.

1 Introduction

The most important design choices an engine company makes are those strategic decisions that determine the final engine core architecture and size. The reasoning behind this is primarily driven by the exceedingly high cost of core architecture development and the fact that these architectures must be capable of meeting requirements as they emerge over time. The risk in designing these engines has meant that engine program launch decisions are becoming more and more dependent on non engineering-related design factors. A company cannot afford to base its decisions on information that does not account for the uncertainty associated with engineering assumptions and customer requirements as well as financial and competitive factors that are critical to decision-making.

Understanding the changing requirements and design uncertainty is only half the problem. Some type of analysis is needed early to consider the broader perspective of design for growth within a product family and how to strategically position the family to maximize its return on investment in today’s and tomorrow’s markets. Furthermore, if one were to assume a rational, capitalistic society, then as a decision maker a global design objective would be to dominate the requirements space and maximize profitability. For these reasons technical and non-technical design issues have to be addressed simultaneously early in design in order to answer questions such as: "how much design margin (for robustness against uncontrollable design factors) is necessary?", "how much growth potential should be built into the product?", "when is a strategic alliance the optimal business strategy?"

Although it may be difficult to answer these strategic questions analytically, this challenge

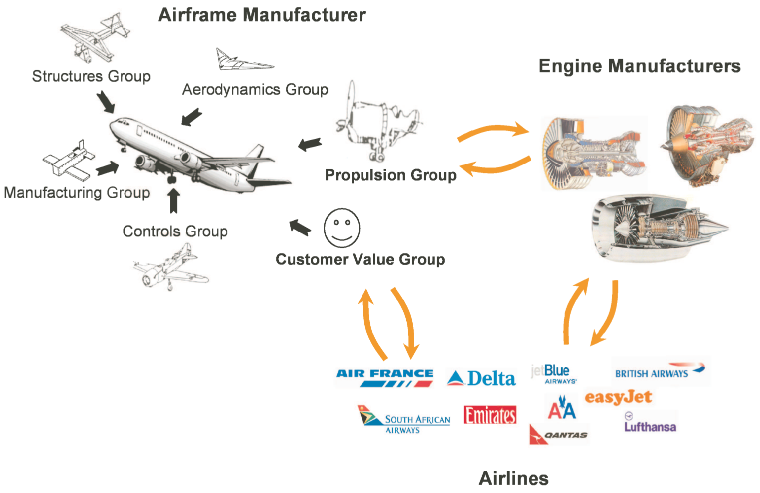


Fig. 1 Players in Commercial Aircraft Engine Design

can be overcome with a framework that gives designers a means to use decision-critical knowledge to model, structure and negotiate solutions within the context of risk and uncertainty and ultimately provide a foundation for exploring strategic moves.

This paper proposes the development of a strategic decision-making simulation environment that is capable of modeling a commercial engine selection process. The environment utilizes business, engineering, and probabilistic tools to address the competitive nature of the problem and to provide mitigation strategies for uncertain solutions. In addition, formulations based on the well-established field of game theory are employed to facilitate the decision-making process through a rapid and transparent payoff simulation. The more complicated and competitive a given market is, the more there is a need for quantitative methods for analyzing business strategies and the influence of engineering decisions on a strategy. It is therefore suitable to borrow some of these algorithms, couple them with the physics of the problem and use them to guide the decision-making process.

2 Engine Design Programmatics

In today's world where affordability precedes performance in design, emphasis is placed on making the right decisions in the early phases of design [1]. The margins on regulations, environmental awareness and life-cycle cost now have more influence on the success of a program than at any other time in the past. Decisions at the managerial or higher level typically determine the design path and are often made by those with limited information or engineering knowledge of the product. The notion of strategic business decision making as part of the traditional design process was not thought of until recently. Commercial aircraft engine design is a typical example of business decision making in which engine manufacturers are competing against one another in a global market in order to capture the largest market share possible. A complex relationship exists between the engine manufacturers and the airframe companies and the airlines, as illustrated in Fig.1.

New design methods and computation capabilities have allowed engine manufacturers to produce highly complex and reliable engines with substantially decreased operating costs. Modern designs however, continue to be more complicated and more expensive to manufacture. Risk is not only a function of the probability of failure but also the cost associated with failing. One approach suggested by Roth is to examine this risk is to identify the main factors that drive the likelihood and cost of failure [2]. The four main areas that have to be examined early in en-

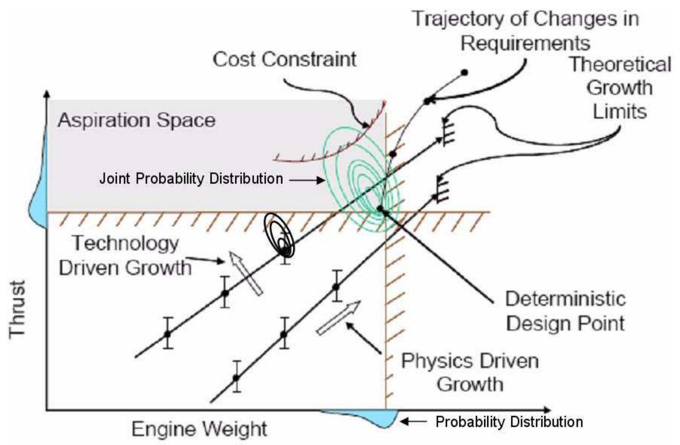


Fig. 2 A Notional Engine Design Space

gine conceptual design are the uncertainty, complexity, technology and business environment.

2.1 Engine Design Uncertainty

There are several probabilistic methods that deal with design uncertainty, requirements uncertainty, economic uncertainty, etc. Whether it is aircraft mission changes or changes in emissions and noise regulations, there are emerging design methods that allow decision makers to select the most robust or flexible design to all these uncontrollable effects of the future. Probabilistic methods are commonly employed to understand uncertain effects in design. Fig.2 illustrates some uncertain characteristics associated with engine design.

The points illustrated in this figure represent specific engines and their associated thrust ranges. The two notional architectures represent two engine "cores" to which changes can be made to create derivative engines. Although the engine design space occupies many dimensions, for visualization purposes two dimensions have been selected and shown here. Two types of engine sizing trends are shown. The first growth trend is physics-driven, by which an engine can be made to produce more thrust at the expense of increased weight. The other growth trend is technology-driven. The exact position of an engine in the space can be described as a probability distribution depicted as solid density contours centered around the nominal engine design point. The likelihood of a particular engine meeting the airframe design requirements can be determined by the intersection of two joint probability distributions. One that describes the airframe requirements uncertainty and the other that represents the engine design uncertainty. Mavris and Briceno demonstrate a measure of design "success" that can be obtained by these probability intersections [3].

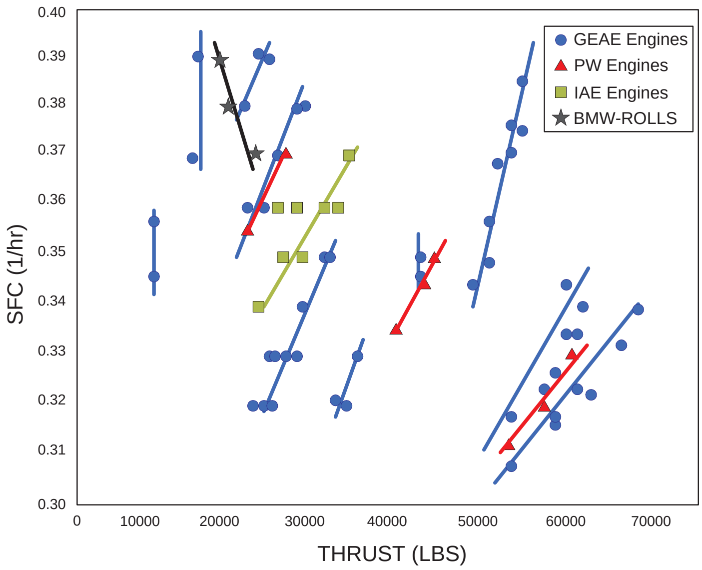


Fig. 3 Product Positioning of North American Commercial Aircraft Engines [4]

The analysis of uncertainty in engine design, discussed in the preceding section, does not account for future engine design considerations. It considers only the impact of uncertainty on a single requirement point without considering the associated uncertainty of evolving requirements. In order to take maximum advantage of emerging markets, designers must be prepared to strategically position their core design relative to their competition and design along the lines of a product family instead of a single application. To better understand this broader perspective and how it interacts with the joint probabilistic requirements/design space previously described, consider Fig.3 which is a representation of the aircraft engine industry as it stands today [4]. Note that families of engines built around common cores largely fall along a line of points, just as was the case for Fig.2. Each point on the plot is an existing engine that represents a single "move" by an engine manufacturer to fulfill an engine requirement.

2.2 Engine Design Complexity

Engine complexity can be viewed as a degree of balance between several competing aspects of design including thermodynamic performance, cost, weight, maintainability, efficiency, etc. Traditionally, the design of propulsion systems was driven mainly by performance and weight with very little emphasis on efficiency and cost. But with the rising cost of fuel and a competitive global market a new design paradigm is needed to address these issues [2].

2.3 Engine Technology Integration

Another trend visible in Fig.2 is technology integration. In this type of growth, thrust may be added to the engine at a constant weight, or even with a weight savings, by the use of new technologies and the expense of increased engine cost. It is possible to see that none of the six existing engines in the two architectures shown in this figure satisfy the requirements; thus, a newly developed engine design will be required. However, infusing new technologies is inherently more risky and their performance in a production product can never be precisely known a priori. With new technologies the core design space must be described probabilistically due to unknown effects resulting from technology infusion.

In addition to probabilistic methods for technology uncertainty evaluation there are well established techniques that focus on rapid identification and evaluation of technology concepts, provide a risk/reward ranking of technology development options and provide a compromise between analysis accuracy and time/cost to conduct preliminary-level technology assessments[5].

If technologies do not successfully improve a design, the process might then involve the modification of an existing engine or the creation of a new engine. The question of which path is best now arises and represents the engineering view of the engine market problem.

2.4 Engine Design Business Environment

In conceptual design there is often a disconnect between decision makers that are at the engineering design level and those managers at higher levels. This often results in failed promises to customers and the accumulation of financial penalties. A strategic business environment is an integral part of the decision making process in these phases, particularly in a competitive market where marginal improvements can be the difference between a multimillion dollar profit or a multimillion dollar failure. Such risks can be mitigated by introducing system thinkers to support engineering scientists as they continue to be pressured by demands in increased productivity and efficiency. McMasters in Fig.4 affirms that "engineering is not done for its own sake, it's practiced in context" to which he concludes that "in the future, the role played by the configurator must now be assumed by an increasing number of the "deep generalists" acting as system architects and integrators." [6] The next sections describe how a strategic business environment can be employed as a simulation platform for engine design.

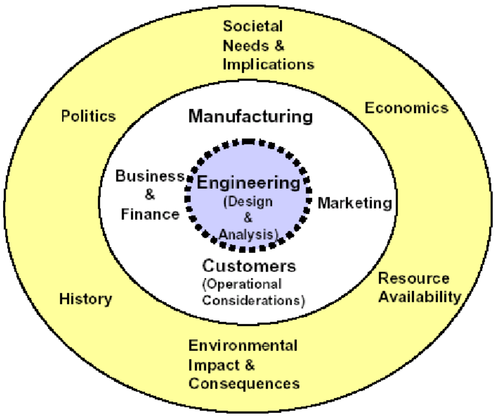


Fig. 4 The Design Onion [6]

3 Strategic Decision Making Framework

The creation of a strategic decision-making environment represents a major research challenge to engine designers. The modeling and analysis of uncertainty in requirements can alone pose significant problems. But the added complexity of uncertainty associated with the larger strategic business environment can make the design of engines a truly formidable challenge. These hurdles are quickly being overcome with the aid of emerging techniques found in fields such as game theory, probability and decision theories, and innovative systems design methods. These promising new advanced analysis methods can be incorporated into a strategic framework as shown in Fig.5. The central element of this vision is a global "plug-and-play" design and decision-making environment. As described earlier, there are four areas of interest in the design of complex systems: Uncertainty, Technology, Complexity and Business. Analyses within these areas are supported by a visualization environment. This tool facilitates the many trade-offs that are analogous with this highly multi-objective space and enables the successful selection of a competitive engine core. The process by which some of these design methods may be employed is described in the following sections.

A key requirement of this model is to link the basic engine design parameters with the overall business metrics and encompass other market variables such as competitor position, maintenance effects, customer value, etc., that impact the return on investment. Creation of such a model that accurately simulates the business environment requires a substantial amount of resources and expert knowledge. The generation of these independent models are therefore not within the scope of this research. Instead, the proposed strategic framework is supported by a simulation environment that uses several industry-generated models and tools as a means to validate the advanced design methods discussed here.

An effective decision-making technique relies on the ability of the engine manufacturer to quantify the uncertainty associated with a given set of requirements and determine an optimum strategy which mitigates the implied risk. The possible management options must be clarified. Since engine design is a process, the development of a new engine is rarely characterized as simply a 'go' or 'no-go' decision. Alternatives to such oversimplification would include deferring a decision, continuing with initial development and then reassessing the project, and other mixed management options. To construct the strategic framework, certain methods need to be created that will support the decision maker in the evaluation of these management options. These methods may be characterized as essential "enablers" for this proposed decision framework. These enablers, critical for the development of the decision making environment, include:

1. The creation of an integrated, physics-based environment for engine design.

2. Game Theory methods to address the presence of competition, provide strategic solutions and to enable designers to efficiently search for such solutions through multi-objective optimization.

3.1 Engine Modeling and Simulation Environment

The modeling and simulation environment consists of a suite of analysis modules/tools that

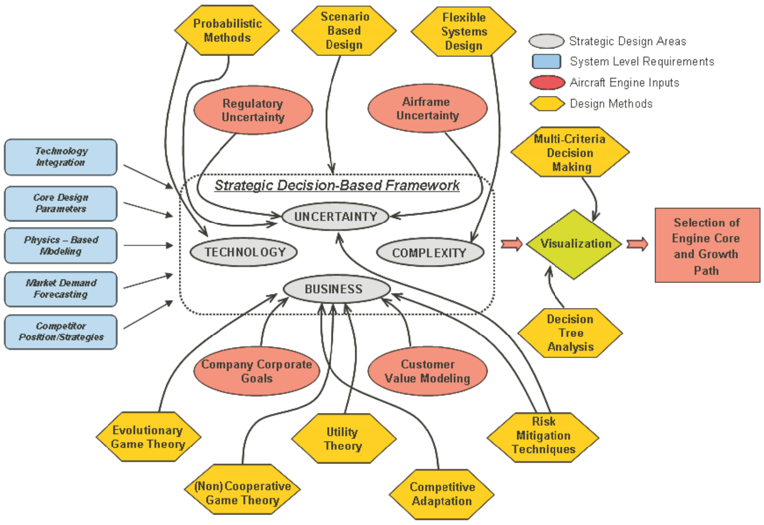


Fig. 5 Strategic Decision Framework

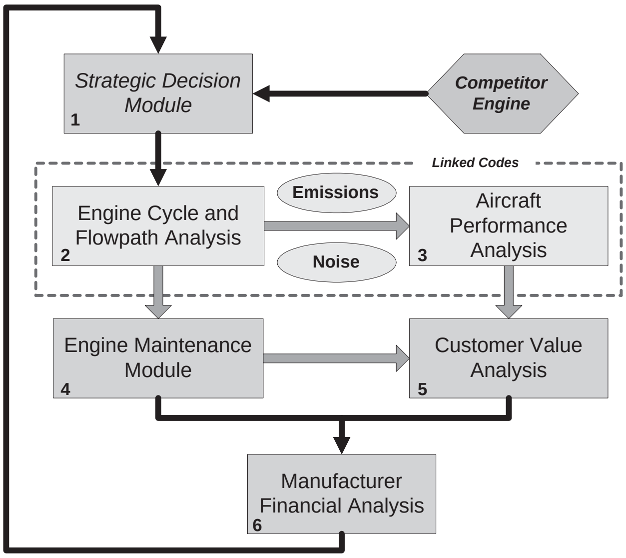


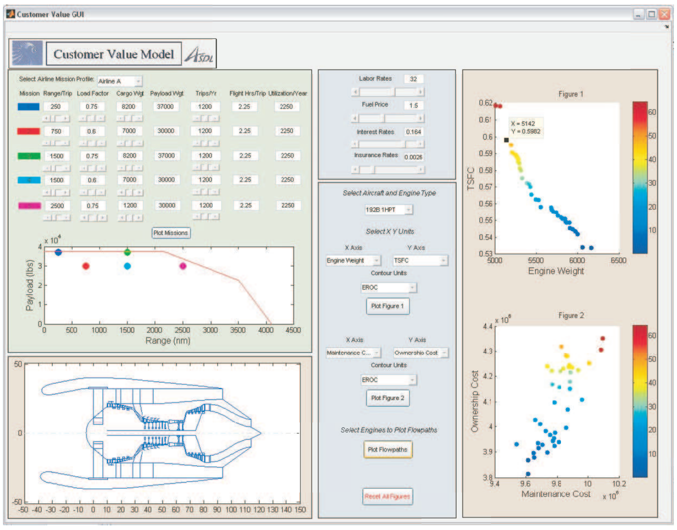
Fig. 6 Engine Modeling and Simulation Process

represent the different aspects of engine design and selection process. The different modules are: Engine Cycle and Flowpath Analysis, Engine Maintenance Model, Aircraft Sizing Model, Customer Value Model, Engine Financial Model and Strategic Decision Model. Each module consists of an analysis method which can be either a physics-based analysis code or analysis method. A schematic of this type of simulation environment is illustrated in Fig.6.

The five main analysis modules that describe the core engine design process are labeled 2 through 6. Module 1 is a strategic decision model that allows the decision maker to switch strategies and monitor the overall progress of the simulation. This is done through a graphical user interface, shown in Fig.7, which is coupled with the modeling and simulation process. The interface is also functions as a customer value model that enables designers to incorporate the characteristics of airline operations into the engine selection process.

The simulation process Fig.6 does not represent any specific engine design program. It was created to characterize the interaction between the different fields that influence the design process of a typical engine program. It is common for engine companies to design engines for different airframe configurations they anticipate the airframer and market may introduce in the future. This simulation environment provides the engine manufacturer with a testbed for new emerging technologies. The process outlined in Fig.6 has the capability of modeling various airframes in order to test competing engines on multiple airframes and over different mission scenarios.

A particular aircraft will typically have a variety of missions requirements throughout its life with an airline. These missions are often not similar in range and payload. For instance, airlines often operate the Boeing 777-200ER over a va-


Customer Value GUI

Customer Value Model

Select Airline Mission Profile: Airline A

Mission	Range/Trip	Load Factor	Cargo Wgt	Payload Wgt	Trips/Yr	Flight Hrs/Trip	Utilization/Year
🟦	250	0.75	8200	37000	1200	2.25	2250
🟥	750	0.6	7000	30000	1200	2.25	2250
🟩	1500	0.75	8200	37000	1200	2.25	2250
🟦	1500	0.6	7000	30000	1200	2.25	2250
🟪	2500	0.75	1200	30000	1200	2.25	2250

Labor Rates 32
Fuel Price 1.5
Interest Rates 0.164
Insurance Rates 0.0026

Select Aircraft and Engine Type: 192B 1HPT

Select X Y Units
X Axis: Engine Weight
Y Axis: TSFC
Contour Units: EROC

X Axis: Maintenance C...
Y Axis: Ownership Cost
Contour Units: EROC

X = 5142
Y = 0.5982

Fig. 7 Customer Value Interface Model

riety of different missions and payloads, ranging from 1000 nm to 6000 nm and with payloads of 40,000 to 120000 lbs. Any combination thereof is feasible, provided that fuel volume and takeoff weight limits are met. Mission mixes potentially have a large impact on engine design since they are expected to perform optimally during every mission scenario.

3.2 Game Theory Implementation Process

To successfully create the efficient decision making environment described above, a general methodology for engine selection needs to be formulated that will require the application of advanced methods to find the best set of strategies possible. One potential technique is game theory. A comment in an article from a prominent management consulting firm says that "The application of game theory is not going to give you a single answer. The best you can hope for is that it forces you to categorize what you know, what you don't know and what the drivers are." [7] The following sections discuss how game theory can be applied to an engine selection problem.

3.2.1 Introduction to Game Theory

Many advances have been made over the past few years in the field of decision-making and new innovative approaches and algorithms have been proposed in the field of game theory. Game theory presents a logical and mathematically based means of approaching problems involving competitors and decision making. A game is a model of a competitive situation, and game theory is a set of mathematical methods for analyzing these models and selecting optimal strategies. Game theoretic methods also provide a basis for enumerating decisions available, evaluating options or "moves", ruling out "moves" that do not make strategic sense, determining the viability of partnerships, and conducting "what-if" analyses for various scenarios. These techniques can be applied to solve most decision making problems by creating games where the following "rules" are established[8]:

- There are two or more autonomous decision makers called *players*;
- Each player has a choice of two or more *actions*;
- A player's *information set* is his/her state of information at the time he or she takes an action.
- A *strategy* is a rule to tell the player which of the available actions to choose, subject to available information, each time he/she makes an action.
- The *payoff* of a game for each of its players can be be defined in either of two ways: a) as the utility received at the end of the game, or b) as the expected utility obtained as a function of the strategy space of a player.

The more complicated and competitive a given market is, the more there is a need for quantitative methods for analyzing business strategies and the influence of engineering decisions on a strategy. It is therefore suitable to borrow some of these algorithms, couple them with the physics of the problem and use them to guide the decision-making process.

The game model itself can contain sophisticated company analysis codes and simplified descriptions of competitors. Game theory may involve the application of simple optimizations of combinatorial problems, including for instance, the application of "competing" genetic algorithms as players in a game model.

The use of game theory in this paper is discussed as a method for assisting the process of selecting commercial engine architectures in the presence of competitive uncertainties. A game theoretic optimization scheme is then coupled with the selection process to evaluate the multi-objective problem that is common in engine design.

3.2.2 Technique Review

There are several types of games and a description of their mathematical implementation in [9]. Game theory has taken a supporting role in decision making for large complex design problems. One approach to engineering design is the "Game-Based Design" method that describes the mathematic principles of rational behavior for decision makers in design scenarios [9]. It combines game theory, decision theory, utility theory, and Bayesian probability theory to assist with the non-subjective rational decision making process. Further research in multidisciplinary design problems has been conducted by employing game theory techniques. An approach to this problem has been to study the interactions in multidisciplinary design as a sequence of games among a set of players, which are embodied by the design teams and their computer-based tools [10].

Game theory is not only prevalent as a decision making tool but also as a multi-objective optimization method. It has been demonstrated how game theory as a design tool applies beyond scalar optimization to the multi-criteria optimization problem. The multi-criteria optimization task is examined not only from the perspective of a single designer but from that perspective of team design as well [11, 12]. The aspect of optimality may be used when a multi-objective design problem has been assigned to several designers or design teams with each designer being responsible for one or more design objectives.

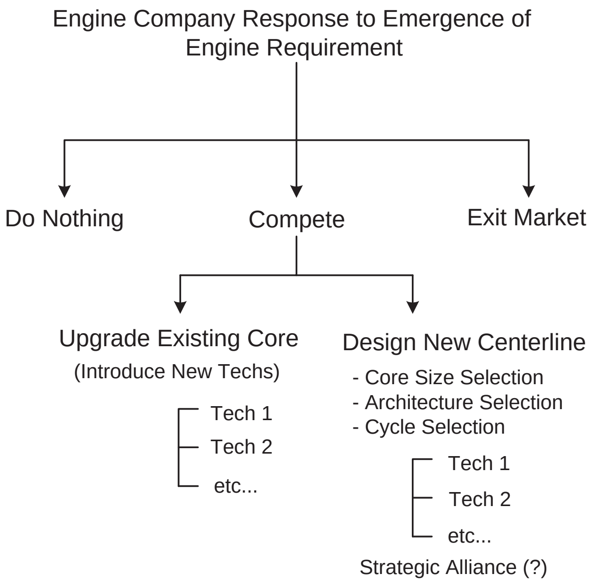


Fig. 8 Notional Engine Tree Decision Game

Decentralizing responsibility in such a way is a natural choice in the design of large-scale systems integration such as aircraft-engine matching. With several designers each with his own objectives, the nature of the optimization process can take several paths and the total design may not be optimal in the sense that a single designer theoretically could do better. Game theory applied to this type of situation provides a method for understanding and perhaps guiding the optimization process. As such, it provides an important management tool for use in decentralized design. The following section outlines an approach for strategic design for an engine design problem.

3.2.3 Game Process for Engine Design

A notional competitive scenario between engine manufacturers can be translated into a game board wherein each competitor has certain strategies that can be carried out. Fig.8 shows a simple example in decision-tree format of the available strategies that a typical engine manufacturer might have. In reality, many more sub-decisions, like resource allocation, will have to be made under each of these. However, this provides a good start to enumerating decisions that must be made initially at the start of an engine program.

The game process as shown in Fig.9 begins with a clear list of design actions available to each engine manufacturer, player, as stated above. The simulation begins with the emergence of a new requirement. This could be in the form of a new airframe or an airframe variant. All pertinent information related to the problem, including any knowledge about the competitor and their position in the market is collected. A comparison is made between the players' engine capabilities on multiple dimensions like thrust, SFC, engine weight, etc., as depicted in Fig.3. Each player must then assess their strategic options and capabilities with respect to these requirements and their competitors' strategic options. This can be done by generating scenarios that are representative of potential strategy combinations.

A new technique called "Competitive Adaptation" uses the natural adaptation mechanisms found in nature as a model for "artificial adaptation" of complex scenarios[13]. In particular, certain optimization techniques such as genetic algorithms and evolutionary game theory[14, 15] can be implemented to create a pool of game scenarios as shown in the middle box of Fig.9.

Once the game board is mapped out and the game scenarios are outlined, they are run through simulation model shown in the bottom box of Fig.9. This primarily consists of the modeling and simulation environments described earlier in Fig.6. The pool of scenarios are modeled through this environment for the purpose of assessing which engine designs are more robust to market and competitive uncertainties. Each player has the ability to individually change the settings/characteristics of their simulation to maximize their market share. The market assumptions are dictated by representative airlines that each have differing operating structures and preferences on the engines. The market share is determined based on how well the engines match the needs of the airlines. For each scenario simulated, the overall market share will be determined based on the airline preferences dialed into the interface tool in Fig.7.

As part of the simulation process, an optimization scheme is implemented by each player so as to search for potential designs that would

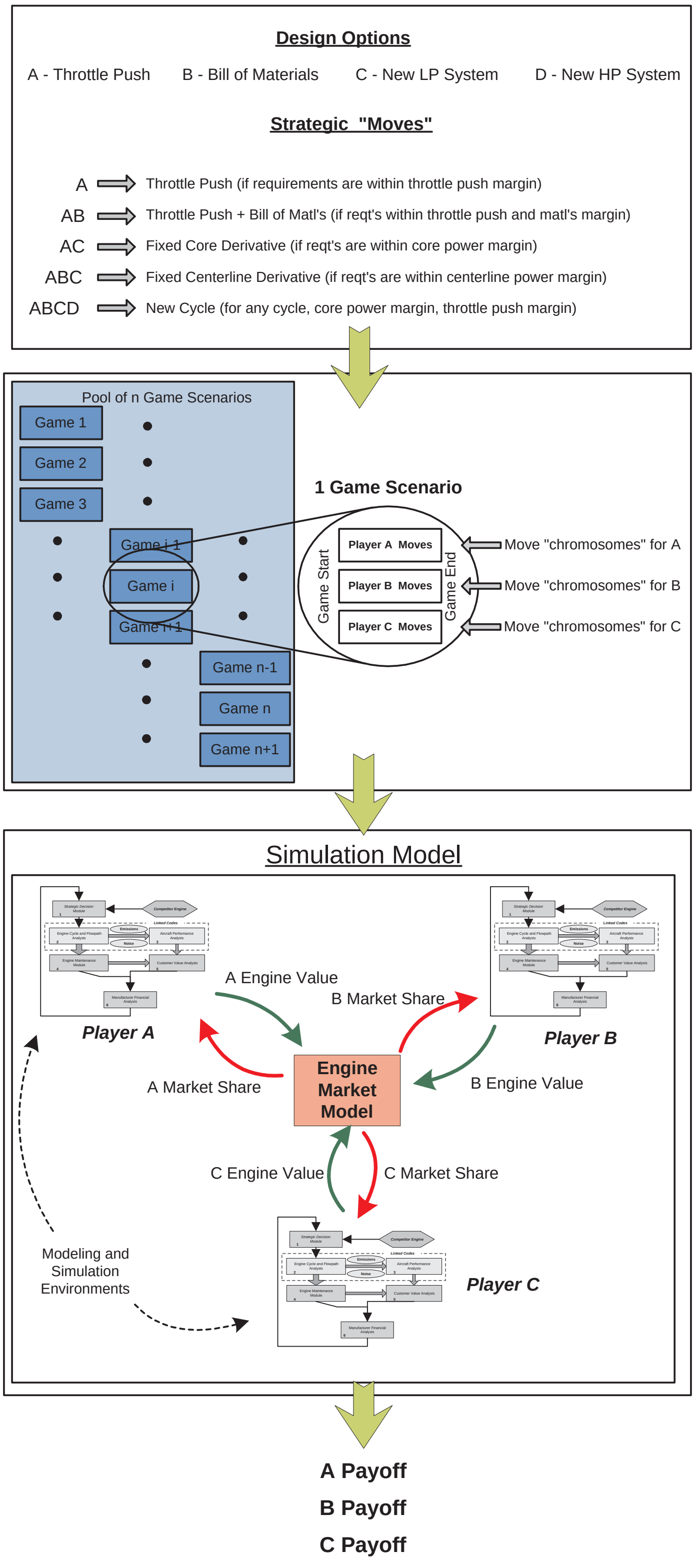


Fig. 9 Game Simulation Process

be more competitive and thus more successful in the game. This optimization process is in most cases multi-objective with a large number of significant variables. This multi-objective engine design problem may be envisioned as a game in which the objective functions are market share and net present value function. The variables are each player's strategy choices and they compete to optimize their position in a system subject to constraints. Economists, in studying competitive systems, have developed theories for games which are readily applicable to engineering design. Two theories have been used to describe the interaction of players: the noncooperative theory, based on the concept of Nash Equilibrium[16], and cooperative game theory, based on the concept of Pareto minimum solution [17].

The fundamental assumption in noncooperative theory of games is that players are only concerned about their own interests. Players select strategies to optimize their position or payoff with no concern of how their choice will affect their opponents or their objectives. In repeated games, players may have the option to bargain or negotiate in order to improve their situation. At the end, there is typically an game equilibrium that has been achieved. This solution is often referred to as a Nash equilibrium. At this equilibrium, no player may improve his objective by unilaterally changing their strategies, as long as the other players maintain their selected strategies. Multiple equilibrium points may exist depending on the order and in which players choose strategies. Theories on first and second mover advantage may demonstrate this effect. Finally, although the Nash equilibrium is generally the "safe" strategic combination for players, there are solutions that exist where players may have better payoff values.

In cooperative game theory, each player works collectively as a group in which each player is willing to compromise his own objective to improve the group solution. A Pareto optimal solution is then achieved select strategies that are as optimal as possible to all players. Unlike non-cooperative theory, each player must select strategies that are beneficial to them but not detrimental to another player. One method is to select strategies such that all players are as far from their worst cases as possible. The best known method of optimizing several objectives while leaving them independent of one another is the minimax method. This entails minimizing the maximum deviation from the objective goals (desired values) with the constraint that the solution be Pareto optimal. A Pareto optimal solution is a solution to a multi-criteria problem in which any decrease in one objective results in a simultaneous increase in one or more of the other objectives.

An advanced approach to cooperative modeling is through the construction of rational reaction sets (RRS) [10]. The RRS of a player characterizes how a player would react to any strategies and variables that other players have. This method is most beneficial if approximated through design of experiments and response surface methodology [18].

These techniques described above are introduced into the optimization phase of the modeling process where the engines undergo design changes and technologies are implemented to improve on the competition. After a competitive assessment is made with the new optimized engine, a decision is made to determine whether further optimization is required or if new design requirements should be introduced into the modeling process. The game simulation becomes an iterative process that allows the decision makers to conduct "what-if" analyses for various scenarios with his/her competitors. An organized framework for decision making is therefore generated by reducing the complexity of engine design down to the critical decision criteria and objectives.

4 Conclusions and Future Work

This paper introduced an approach to commercial engine selection that can benefit decision makers under time constraints and with influential sources of uncertainty. The method proposed assists decision-makers in answering global questions regarding the basic architecture and core size/growth path decisions. A variety of game theoretic techniques were discussed as a way to optimize engine architectures in the presence of competitive uncertainty and as potential means to quantify and evaluate the influence of present and future market competition on the decision making process.

Future simulation studies will involve exploring the probability and timeline of the introduction of derivative aircraft in order to assess long-term competitiveness and assist in core size and architecture selection. Engine sizing strategies may differ significantly if an engine is designed for maximum performance as an entry-into-service engine versus one that performs well over a spectrum of derivative aircraft. An example is demonstrated for the regional jet market in [19].

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