SCENARIO-BASED DESIGN COMPETITIVENESS EXPLORATION WITH SYSTEM DYNAMICS

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Abstract

The commercial aircraft market has been hotly contested in recent years. The challenge for each of the manufacturers has been to not only meet the demands of the market and regulations but also to meet or exceed the competition in order to either keep or expand market share to ensure long term profitability and stability. To meet this challenge it is necessary to be able to predict the requirements of the near and mid term aircraft market. This requires integrated high fidelity market models and forecasts as well as high fidelity conceptual design studies that address key issues ranging from general economic conditions and commodity prices to future technological developments.

The problem addressed here is a traditional disconnect between marketing and engineering partly due to the difference in thinking cultures. To bridge this gap a new method is proposed that integrates conceptual aircraft design into a system dynamics market model. This model allows two aircraft to compete in the same market while allowing the definition of scenarios further detailing the market for example through varying macro-economic conditions. This model is then calibrated against existing data. The inherent model uncertainty is addressed through a probabilistic treatment that uncovers the potential variability in the defined scenarios.

1 Introduction

The development of the commercial aircraft market in recent history has seen significant ups and downs as well as significant structural changes. This volatility of the transportation sector is fairly well known and partly thought to be caused by amplification of general macro economics trends such as gross domestic product growth and commodity prices, especially the heavy dependency on oil and fuel prices. The structural changes were largely driven by significant consolidation that resulted in the emergence of two principal competitors in the market for large commercial jet transports, namely Boeing and Airbus.

These two competitors try to compete and satisfy market demands while being constrained by existing and potential future regulations that might emerge from further future noise and emissions stringencies or market based options that might be introduced. The ultimate goal of either company, however, is to increase their respective market-share, which does not accounting for the advantage of not being market leader. This more easily enables receiving a number of government subsidies in various forms.

Furthermore, it is a very difficult task to reconcile the different views on the commercial aircraft market, especially when there is no agreement on what even the fundamental trends are such as overall demand and size distribution. This is especially obvious when looking at either company's market forecast [1, 2]. There is already a very fundamental difference that puts either company at the other end of the spectrum in terms of the expected size of the market for certain seat classes of aircraft.

On one hand, Boeing is forecasting a departure from the hub and spoke model used by many airlines to more direct flights. This will result in a need for more efficient and flexible lower capacity commercial transport aircraft. On the other hand, Airbus sees a more and more constraining factor in flight movements possible at certain key hub airports. Therefore, they forecast a need for more very large transports in order for airlines being able to meed future air travel demands. Both competitors are probably convinced that their forecast and the decisions based on them are correct. In reality, however, there is only one possible outcome. This does not mean that one is wrong and the other is correct. More likely the answer will be in between both extremes or a mix thereof, which could essentially mean both can come true.

Furthermore, there could also be a fundamental shift of the underlying dynamics of the entire air travel market either through sudden "catastrophic" shifts or less abrupt shifts in the fundamental way in doing business that could mean an entirely different outcome. Such fundamental shifts are more likely the longer the forecasting timeframe. Additionally, it is basically impossible to forecast such fundamental shifts correctly or to simply forecast that such shifts will happen in certain circumstances outside of simply stating that even the most thorough forecast is likely to be unable to cope with such changes.

This brings up the point of trying to design aircraft to fit such forecasts that are uncertain in their very nature. Until very recently, design requirements were or are agreed upon by experts or committees thereof. This can still be the case. These requirements were then handed to conceptual designer. However, this process did not involve a rigorous analysis outside of expert opinion. There is a chance that the initial sets of requirements are not understood sufficiently or in the worst case are wrong. Furthermore, it also can be very common for the original requirements to be out of date by the time a project is launched which then resulted in changes very late in the program or a suboptimal final system.

Very often aerospace development programs span a significant time period. Completion frequently takes many years or even decades. During the duration of these programs there can be significant developments in technology as well as in society as a whole. These changes potentially mean that initial design requirements are completely invalidated because the basis for them has changed and the initial need for the proposed system has now shifted.

This fundamental problem is the basis of what robust design tries to address. Robust design means that a given design needs to be flexible enough to still be able to accommodate later changes in requirements [3]. A robust design is inherently more adaptable to evolving future needs and therefore is more likely to be competitive when it finally comes to market.

In light of this desire, it becomes important not only to carefully examine initial design requirements, but also to integrate disciplines. This integration is a key enabler for improved understanding of requirements because it enables higher fidelity trades across disciplines, which allows presentation of as much knowledge as possible in the earliest stages of design. This allows the designers and key decision makers to make more informed decisions to avoid potential pitfalls that unknowingly commit a certain program to outcomes that eventually will require major changes very late in a program.

Furthermore, design requirements have typically been treated as static. These requirements initially might be unchanged or only deviate by a small amount from the initial requirement definition over small time periods. However, with the increased duration of development cycles, this is increasingly no longer the case. This is partially addressed by robust design by introducing a probabilistic treatment into the process which addresses some of the problems of traditional fixed requirements by showing a more comprehensive assessment of requirements and the involved uncertainties. However, this method is also not always able to assess the uncertainties properly. For example, in cases where certain economic variables have a large uncertainty attached to them, the resulting uncertainty for the entire system can become overwhelmed by the economic uncertainty that results in the inability to make a decision based on the results of the robust design process.

2 Problem Definition

2.1 Forecasting and Scenarios

Forecasts of the future are notoriously unreliable and highly dependent on assumptions that naturally lend themselves to a probabilistic treatment. The problem that arises, however, is that in many cases the underlying uncertainty becomes overwhelming. One example is the uncertainty in fuel prices, which over even relatively short periods can be very significant. When this uncertainty is propagated throughout a design analysis with a robust design as the final goal, the result very commonly is overwhelming uncertainty. This prevents the results from being useful in decision making for achieving a robust design, unless the decision is to not invest due to the risk that presents itself. This is clearly not desired and has to be improved upon.

One way to explore future risk is to define a set of scenarios based on certain underlying assumptions about external factors. This means that a small set of initial and future assumptions is created and analyzed. Each set is then defined as a single scenario. The scenarios are commonly chosen based on current best effort estimates of likely or possible assumptions or based on low, medium, and high range estimates essentially defining low and high bounds as well as a mid point. This is essentially equivalent to performing a sensitivity analysis on a time series forecast.

The previously mentioned probabilistic treatment assumes a fixed uncertainty distribution of the fuel price. The uncertainty of the fuel price is fixed in time due to this assumption. In reality, however, the fuel price will not exhibit such a wide range of variation. Tomorrow's fuel price does not have the same probability distribution as that of a year from now. Additionally, today's fuel price has a direct bearing on tomorrow's fuel price; that is, fuel price exhibits a time correlation. Or when expressed in mathematical terms, the uncertainty is not independently and identically distributed. The fuel price cannot change infinitely fast; rather it has some amount of inertia. This inertia causes any future values of fuel price to be correlated to past and current fuel prices.

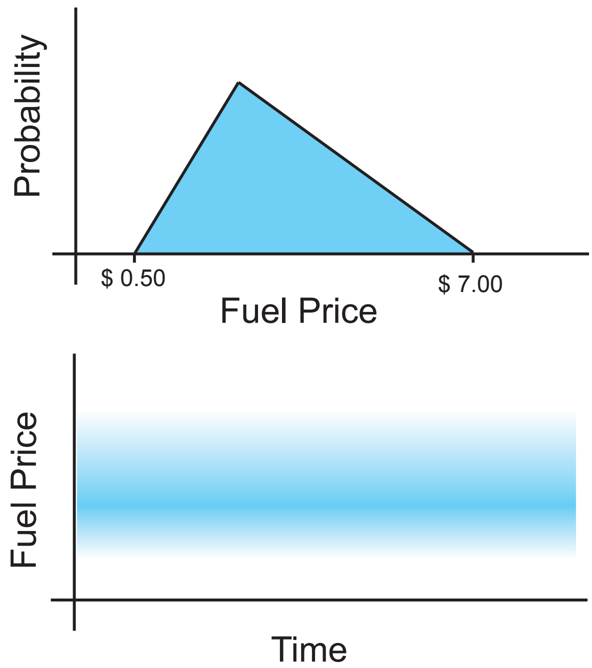

Fig. 1 Static Probability Distribution Assumption

This means that it is insufficient to simply extend the fixed probability distributions to time variant probability distributions. Instead it is necessary to define proper statistical processes that allow a more accurate and ultimately more narrow uncertainty model in the design analysis. There exists a vast body of knowledge in modeling the time based uncertainty in commodity prices. The goal of this is to reduce the overall system uncertainty stemming from external factors such as fuel price that at the end of the robust design simulation process produce overwhelming uncertainty that prevent decision makers from coming to a meaningful substantiated decision.

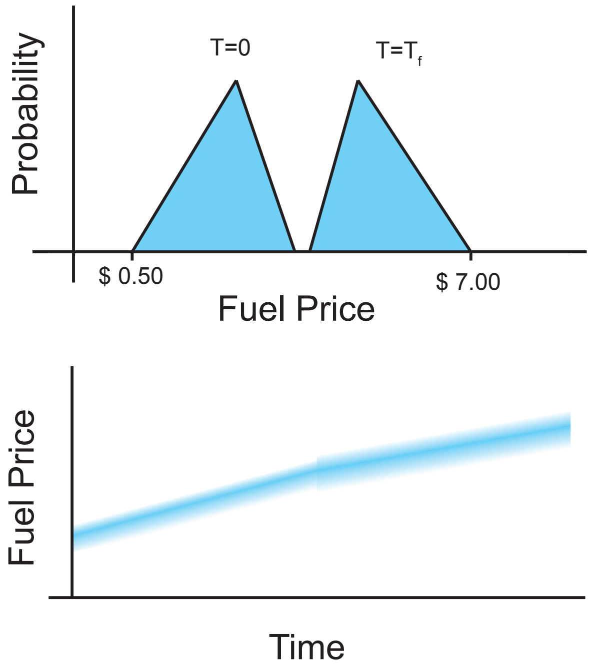

Fig. 2 Time Variant Probability Distribution Assumption

This shows that a comprehensive probabilistic treatment that addresses a number of scenarios could be a promising approach towards tackling the overwhelming uncertainty faced by complex engineering problems through mostly economic factors.

2.2 Competitive Market Model

The other element required for addressing the question of future success of a given concept is a competitive market model that is capable of representing all the necessary features such markets exhibit. Therefore, it is necessary to define an environment that allows the exploration of the system competitiveness with regard to changing requirements and market conditions while being integrated into very early preliminary design phases. Since such markets feature a number of dynamic behaviors, a prudent approach would be to utilize a method that allows the specification of such dynamic features. The method proposed here is to use a high-level, system dynamics model that captures the dynamics of a commercial transport aircraft market. Previous attempts have been made to model the overall size of the commercial aircraft market [4]. The most promising attempts utilize a system dynamics model connecting the major drivers and stakeholders. The key to a successful model of this kind, however, is the calibration against real data and as necessary an extension to be able to match the existing historical behavior.

3 Model Formulation

The simulation model that can meet these requirements has to be created at a very high level, since a bottom up modeling approach would require tremendous effort and large amounts of data. Therefore, a top down modeling approach is a better fit for this particular challenge. Such a top down approach that at the same time can create a time dependent model that includes a probabilistic treatment that does not require enormous computing resources can be found in system dynamics.

3.1 System Dynamics

System dynamics is a method of analyzing and simulating complex systems that emerged in the 1960s and 70s to tackle the rising concerns about unmanageable complexities in real existing systems and processes. This was accomplished by applying control system theory to them. This eventually was then termed "Industrial Dynamics". The system in the name originally referred to a industrial production and distribution system [5]. This was one of the early efforts to model the dynamics of industrial system; hence the name. Modelling initially was limited to supply chain systems but then was extended to organizational structures and project management.

System dynamics was then eventually applied to much larger systems such as urban models [6] or even global models [7]. In fact system dynamics models were the foundation of the work on limits to growth [8] and on urban growth, renewal, and traffic planning. It has since been applied to a large variety of problems and was able to provide insights into causes of failures, potential strategies, and policy choices that actually have the desired effects. These models were later revisited and within limits still showed good agreement with what really happened.

System dynamics builds on four foundations. The first foundation is information-feedback control theory, which has its roots in design and understanding of engineering control systems. The second foundation is the modeling of underlying decision-making processes. This means that such a model strives to capture a system in such a way that it includes any relevant decision-making processes and key variables that represent such choices.

The third foundation is the experimental approach to system analysis which attempts to take the underlying concepts and make them easily accessible. This is primarily done by representing each element of a system model visually to facilitate the overall understanding of the connectedness of all elements and their influence on each other. Models are generally created and shows with a mostly standard visual representation [9].

The fourth and final foundation is the use of digital computer simulation. Forrester was the first to make extensive use of computer technology to simulate the system models created. This is important because it allows numerical simulation of the system model at hand with sets of differential equations involving key processes and parameters. The speed of calculations is much increased compared to earlier analytic or manual approaches. This is a fundamental feature necessary to be able to experimentally explore system models. In his initial work Forrester actually describes the development of a system dynamics compiler called DYNAMO[5]. This compiler was key to being able to specify system dynamics models as sets of equations. However, computer technology at the time was still in its early phases.

Since then much progress has been made and currently a number of commercial computer software packages exist that readily allow visual model construction through a graphical interface. The package used here is Vensim ™[10]. These software packages allow the results of a simulation to be obtained relatively rapidly. Such a quick turnaround time essentially allows repeated experimentation with the system model. This experimentation then can yield insights into the accuracy and stability of the system model. Furthermore, a number of scenarios, each with specific setting of external parameters or deliberate policy choices, can be simulated in rapid succession. This not only enables a learning process that yields insights into the overall behavior of the system model (and therefore the system if the model is sufficient and has been calibrated) but also readily allows the use of probabilistic analysis to show the likelihood of these scenarios.

3.2 Market Model

System dynamics models are normally constructed in a very methodical manner out of a small number of standardized elements. The details of this process and the model elements are not described in detail here. However, this method is described in detail in Sterman's book and instructor's manual specifically intended for teaching system dynamics[9][11].

Therefore, here this work will be limited to the description of the specific market model created to address this specific problem. This model is based on a competitive model described by Sterman [9]. However, the model originated earlier from a MIT memo [12]. In both cases it was used in an attempt to model the battle of video cassette recorder formats that occurred throughout most of the 1980's. The competing formats - VHS and Betamax - were locked in a battle for market share. The outcome was influenced by a number of important variable such as price, capabilities, and most importantly a very strong commonality effect created by secondary markets for cassettes as well as movies for purchase and for rent. The eventual winner was the VHS.

The model used here is loosely based on this model. Figure 3 shows a model in which the graphical nature of the system dynamics model serves as additional documentation of assumptions internal to the model. This is accomplished by directly showing the linkages between key actors and important functional relations between key variables. In this model the market is dominated by two competing aircraft. The market share of each aircraft is heavily influenced by the "attractiveness" of each aircraft, which is calculated from several elements. This is accomplished through the use of an overall evaluation criterion (OEC). An OEC represents a relatively straightforward way of combining a number of different decision variables into a single criterion by normalizing each of the included variables, adjusting for minimizing or maximizing where desired and then finally introducing a set of weighting factors for each of the included variables. The result is a single parameter that can be directly used to differentiate among a number of competing systems as long as the actual preferences are expressed correctly through the individual weighting factors. The choice to use a relatively simple OEC was mainly motivated by the ease of the formulation and the readily adjustable weightings which were used later to calibrate the model to the existing sets of data. A large body of often superior methods is readily available and can be implemented if desired; however, this is not the focus of this work.

In this model superior "attractiveness" results in additional sales of the product, so it is essential to understand which of the various decision attributes are fed into the attractiveness and how and why they were selected. One is the commonality of each product, which is the advantage derived from utilizing one and only one type of aircraft instead of two or more. This advantage is the result of a reduced number of spare parts, training hours, and personnel that directly results in lowered cost. The year of introduction is used to zero the attractiveness of each aircraft in the time prior to its market introduction. The overall market is represented by the total demand, and this is independent of the year of introduction. Therefore, a later introduction means that one of the competitors cannot capture any of the market prior to that. The other major elements are comprised of several variables important to the customer, in this case the airlines. This is where the conventional aircraft design analysis comes into play to drive the system dynamics model.

The integration of traditional aircraft design analysis directly into the model involves a large effort to connect the appropriate variables and codes into the model. Additionally, direct integration of analysis codes is computationally very inefficient due to the large number of calls that the numeric differential equation solver requires of the analysis code. This becomes even worse in an subsequent probabilistic analysis that – depending on the method used – has to run the complete model many times. Even more troubling, the analysis codes tend to have discontinuities or non smooth regions in the outputs they create over a large range of variation in input variables.

The solution to this was to follow the response surface methodology and separately run the analysis code according to a design of experiments. The results were then used to create a set of response surface equations that by their very definition represent a set of quadratic polynomials that not only guarantee a smooth and continuous variable space but also are inserted into the model relatively easily and are computationally inexpensive.

In this model the aircraft cost and the required yield per revenue passenger miles for each of the two aircraft is represented by a response surface equation that in case of the yield is dependent on the fuel price. Airlines normally simply hedge with options against fuel price changes such that price fluctuations are contained within a more or less defined band. Therefore, fuel price changes only enter into the longer term planning of airlines. The detailed model of the fuel price is shown in Figure 4. This model is directly based on the model described by Sterman [9]. The model is essentially a model for a probability distribution over time that smoothes the higher frequencies, and therefore has a time correlation, which is true of fuel prices. This means that future fuel prices are dependent on previous fuel prices. The magnitude of this correlation is expressed through the correlation time. This suppression of high frequency noise with a linear

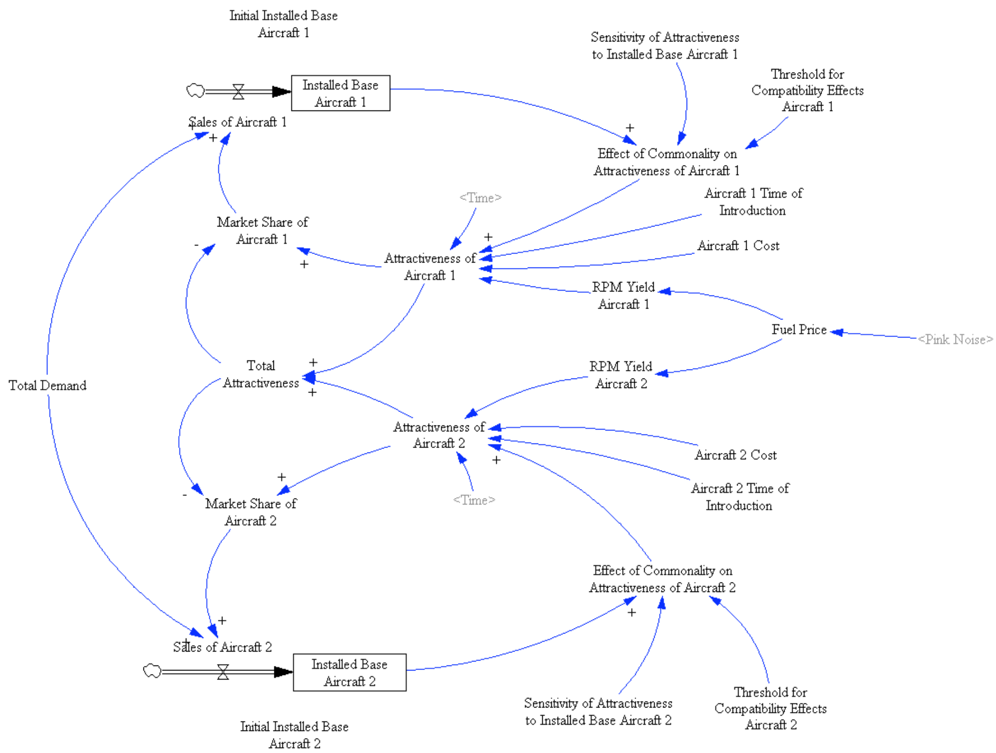

Fig. 3 The System Dynamics Competition Model

drop of amplitude with respect to frequency is called "pink" noise. The only addition to this model is the introduction of a drift rate. This rate essentially represents a long term drift in the fuel price, which essentially can be used to model a consistent rise in the price of fuel. This rise is shown in Figure 5 which shows a single run output overlaid over a contour plot of a monte-carlo generated time dependent probability distribution that shows varying levels of confidence. The main parameter varied here is a uniform distribution over a small range of drift rates.

This model then enables the future tracking of the market performance of a proposed concept while competing with one competitor's product. This is achieved by tracking of the sales of product over the simulated time frame. The outcome is not only affected by cumulative effects of market share, but also by various scenarios affecting the product attractiveness to the customer.

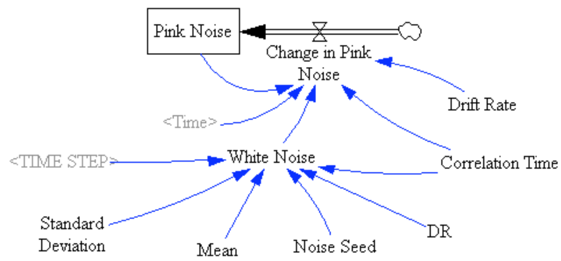

Fig. 4 Pink Noise Model for Fuel Price

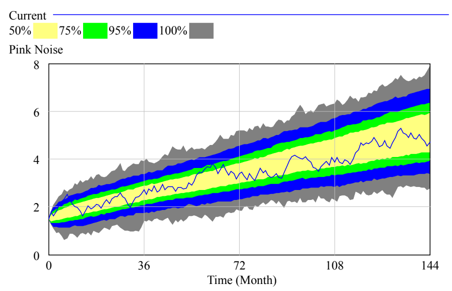

Fig. 5 Probability Contours for Fuel Price

3.3 Aerospace System Selection

The proposed demonstration of this model requires an existing aircraft competing against a comparable version of a competitor. Additionally, market data should be available to be able to test and calibrate the model against the existing data. To this end two comparable aircraft that have been in existence have been selected in the 225 seat medium range class, the Boeing 767-400ER and the Airbus 330-200. For this purpose the delivery date data was used to represent sales because order dates tend to represent sets of aircraft where airlines order a large number of aircraft at once. Dates of first flight are equally not ideal either because they more closely represent the production capabilities of the respective production lines. Figures 6 and 7 show the historical delivery rates of the respective aircraft.

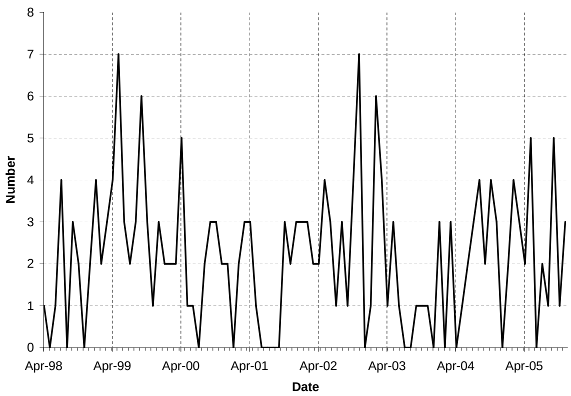

Fig. 6 Airbus 330-200 Delivery Rate

4 Results

4.1 Calibration

After calibrating the model it was possible to closely match the actual sales data. Until the end of 2005 the total market size was 256 aircraft sold since 1998. 202 of those aircraft were Airbus 330-200, and 34 were Boeing 767-400ER. The results of the model for the installed base for each aircraft are shown in Figures 8 and 9. As can be seen the final cumulative sales are very close

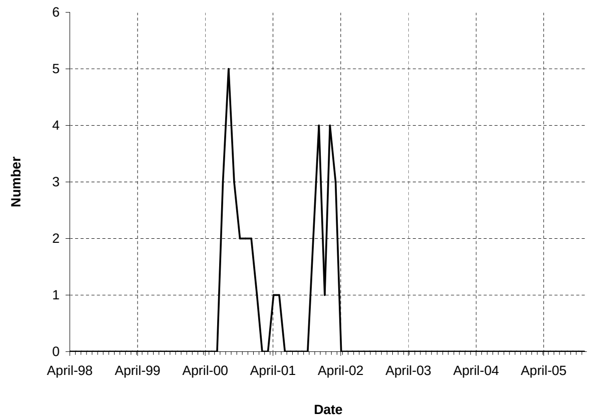

Fig. 7 Boeing 767-400ER-200 Delivery Rate

matches. The result also matches the peak in deliveries seen in Figure 7 soon after market introduction. However, there is still a discrepancy in the fact that there were no 767 sales in the last 3 years, whereas the model shows continuing sales albeit at a lower rate that right after market introduction. The reason is that Boeing stopped offering this particular 767 model and instead offered the 787-9 as a future replacement model.

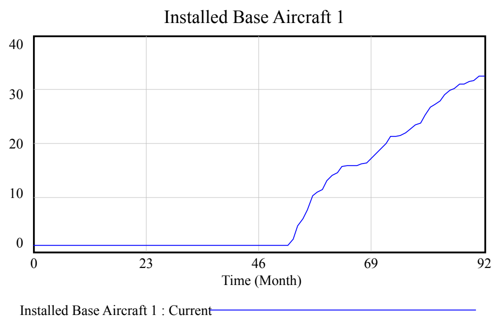

Fig. 8 Cumulative Sales of Boeing 767-400ER

4.2 Forecasting

The goal of the forecasting exercise was to demonstrate that a probabilistic treatment of scenarios can yield insights into the market behavior of each of the aircraft in the model. For this reason a monte-carlo analysis of the competitive market model was performed. The parameters

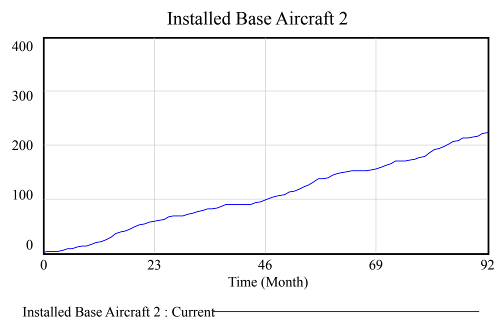

Fig. 9 Cumulative Sales of Airbus 330-200

that were varied in this analysis were varied according to uniform distributions. The uniform distributions signify the fact that there is no *a priori* knowledge about the likelihood of a particular setting. The parameters used were the fuel price drift rate and the parameters used for expressing the strength of the commonality effect.

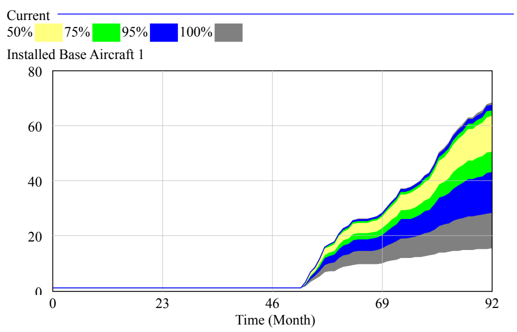

Fig. 10 Cumulative Sales Scenario of Boeing 767-400ER

The results of this analysis are shown in Figures 10 and11. These contour plots show the variability of the cumulative sales for each of the aircraft. The effect of the variability in the sales of the Airbus 330-200 is much smaller, especially before the introduction of the boeing 767-400ER. This is partially due to the model, but also due to a limitation in the modeling software. This limitation unfortunately means that it was not possible to assign probability distributions to external data tables such as the one used for the total market size. This limitation can be overcome by manually inputting the external data and creating

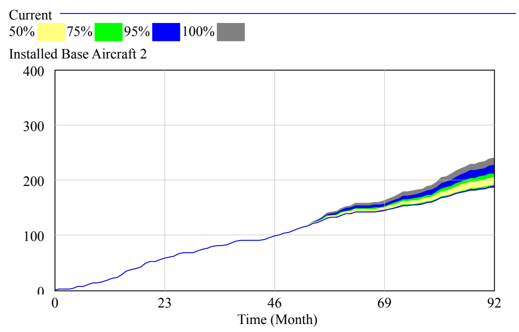

Fig. 11 Cumulative Sales Scenario of Airbus 330-200

an internal lookup table instead, which unfortunately represents a significant effort for a small gain and therefore was not pursued here. Nevertheless, this model does show the increased variability in the market in the face of competition.

5 Conclusion

This work demonstrates that it is possible to create a meaningful model of a competitive market that incorporates aircraft design analysis and external factors such as fuel prices. It was further possible to calibrate the model such that the model relatively closely matches known historical behaviors. The model currently is somewhat limited in the factors that make up the attractiveness of each aircraft to the airlines. The next step in improving this model will be to include more of these factors which should enable an improved agreement between model and historical results. Even with its current limitations, the model demonstrates that it should be possible to expand this model to include actual design parameters. Once that has been accomplished a set of future aircraft with certain design choices can be modeled. Since this then establishes a direct link between design choices and potential market success, it will then be possible to make true system tradeoffs between technical choices in the face of market forces such as competition and commodity prices. This can be of great value because it will allow exploring the market model for particular ranges and choices of parameters and the resulting market success. This should give guidance to aircraft designers what kind of aircraft is favored by the current market and what kind of changes have to happen in the market for a particular new or even revolutionary design to be successful.

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