The Effect of Improved Aircraft Efficiency On Helicopter Sales
Using System Dynamics Modeling

by

Steven David Weiner

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ABSTRACT
As the helicopter industry has tried to reinvent itself after the Cold War, it has become apparent that the traditional competitive discriminators used for successful military products do not apply directly to the emerging markets. Improvements in aircraft efficiency, typically represented by payload-range capability, can still provide a competitive advantage, but these improvements can also be tempered by commercial government regulations intended to improve attributes other than aerodynamic performance capability. These regulations have the potential to severely impact the sales of current and future commercial helicopters and other rotorcraft.

This study uses System Dynamics modeling to investigate the effect of improved aircraft efficiency on sales. Interviews provided clarification regarding the client's fears, and also provided the variables to be investigated, along with reference modes and momentum policies. This information generated three hypotheses as to the possible system behavior. A Vensim System Dynamics model was created to explore these hypotheses.

The model uses separate modules for R&D development and efficiency improvements, workforce makeup, workforce location, regulation imposition, competitive advantage, technological risk and information quality. Three specific types of potential government regulations are modeled to investigate the effect of these policy changes on the basic sales model, and to determine if technology improvements can provide a means of modulating the sales impact. The three regulation areas explored are exhaust gas emissions reductions, external noise reductions, and fuel economy improvements.
The model implementation used lookup tables wherever possible to enable adjustments for platform type and size, workforce makeup, regulation severity, and in general to provide flexibility to accommodate changing technological, market and client company conditions.

An 8 year time period was investigated using the Systems Dynamics model. Parameter variations were compared to determine those with the greatest effectiveness on unit sales. Several projections of behavioral response were then produced for differences in structure due to regulation imposition. Aircraft efficiency improvements alone were not sufficient to prevent sales degradation within the time period of interest. However, using the sales sensitivities to other parameters, a structure change recommendation for the client company was determined that was effective in maintaining sales. The recommended structure changes included development of technology improvements to aircraft efficiency, workforce process changes and increased lobbying activities. These changes could be easily implemented by the client company in the near term.

Thesis Advisor: Dr. James H. Hines
Professor of System Dynamics
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1.0 Summary

Vensim software has been used to create a System Dynamics model to provide insight into the sales behavior of the rotorcraft industry. The structure modeled includes representations of the R&D process in the client company, workforce and hiring details, regulation imposition by external agencies, information maturation and dissemination, technical risk, and the portion of revenues used for technology development. The client company’s fear of significantly reduced sales with the present system’s structure is supported by the baseline model behavior.

Sensitivity studies utilizing the modeled variables provide recommended structure changes that produce significantly improved sales trends over the time frame in question (1999-2008). These changes can readily implemented at reasonable cost, and without undue disruption to the company’s current structure and culture.

2.0 Background

Igor Sikorsky has been quoted as saying “The idea of a vehicle that could lift itself vertically from the ground and hover motionless in the air was probably born at the same time that man first dreamed of flying.” (Reference 1). Projections of the future from the 1940’s and 1950’s show helicopters in every garage, with people commuting in their personal flying machines. Although the helicopter has in fact become a practical transportation device, the easily attainable, personal aircraft vision of times past has not come to fruition, and neither have the expected sales. In fact, the limited global market for helicopters and rotorcraft, in combination with extreme competition in the current global economy, has resulted in significant consolidation within the rotorcraft industry. The remaining firms will face continued competition for market share for the foreseeable future. In order to survive, the remaining companies must pursue every competitive advantage for the products and services they intend to provide. Please note that “rotorcraft” will be used to describe vertical takeoff and landing (VTOL) aircraft in this study. All current commercial VTOL aircraft use rotors as their primary lift and propulsion device, and this is assumed to continue to be the case in the time frame investigated here.

Projections for twin turbine engine commercial rotorcraft sales show the sales trend of the 1994-2008 time frame peaking within the next 5 years at approximately 350 sales in 2004 and then slowing to a 300 aircraft per year rate by the end of the time investigated (Figure 1, Reference 2). The 300 aircraft per year level has a total value of between $1.8 and $2.0 billion US dollars. Further expansion has been hampered by several factors. These include the infrastructure needed to support rotorcraft, competition from existing transportation networks, noise concerns, safety concerns, dilution of the market by surplus military rotorcraft, total costs, and the advent of
commuter aircraft with performance capabilities overlapping the upper end of the rotorcraft envelope, among others. These factors are described in detail in the following paragraphs.

![Twin Turbine Engine Helicopter Sales](image)

**Figure 1**

2.1 **Infrastructure**

A major operational advantage of rotorcraft is that, unlike fixed wing aircraft, they do not need large investments in real estate in order to start revenue producing operations. Within limitations, almost any open area with an unobstructed space larger than the vehicle’s total rotor diameter will do. There are some operational restrictions regarding entry and exit to the landing space, but compared with an airport intended to handle conventional aircraft, they are relatively minor. The landing space, if used as a regular landing zone for scheduled operations, must include some safety equipment, but in general almost any unobstructed area will do. The reason there isn’t a heliport on your street corner lies with noise, safety and cost concerns. In a 1994 survey conducted by Rotor & Wing magazine (Reference 3), noise and safety were ranked as the two biggest problems with respect to rotorcraft public image by the respondents, with 50% and 29% of the responses noting these two attributes, respectively.

2.2 **Noise Concerns**

Rotorcraft are noisy. The current generation of medium weight (6000-11000 lbs takeoff weight) helicopters produce external sound pressure levels on the order of 85-100 dB (decibels). This sound level is not something people usually want in their own backyards. For comparison, an
average living room is 65 dB, a metal wheeled subway car can be 100 dB or louder, and jet airliners at takeoff can approach 130 dB (Reference 4). Sustained exposure to these levels are not only an annoyance, but can cause permanent hearing damage. As a result, a series of noise regulations have been implemented by most countries operating rotorcraft. These regulations usually place a dB limitation for operation of rotorcraft in specific flight regimes. The regulations specify both the levels and the measurement procedures (microphone locations, approach speeds, weather conditions) and in general have limited the number and proximity of rotorcraft operations in several geographical areas. The United States regulations are described in References 5 through 15. In general, the U. S. regulations mirror levels set by the ICAO (International Civil Aviation Organization) and vary according to aircraft takeoff gross weight.

The ICAO was established by the United Nations to ensure quality and consistency among international air transport providers. The standards set by the ICAO are voluntary, but both the ICAO emissions standards and acoustic levels have been used as benchmarks by the FAA (Federal Aviation Administration) in setting US regulations. For an aircraft in the 11000 lb class, the ICAO standards specify that approach levels (as in approach as part of the landing flight path of the aircraft) are to be no higher than 98.3 EPNL dB. EPNL is the Effective Perceived Noise Level. Takeoff operations are limited to 97.3 dB, with flyover limited to 96.3 dB. Rotorcraft in the 6000 lb. class must meet flyover levels of 89 dB.

Other countries have more stringent requirements. Switzerland set limits that are -3 dB less than the ICAO standards for each weight class. There are at least two rotorcraft flying today that can meet this reduced level (Reference 16). However, Hong Kong limits levels to 65 dB for any profile, with measurements taken outside structures in residential areas, and inside structures for commercial areas! It is possible to meet this requirement (the client discussed here has at least one product capable of meeting the Hong Kong levels) but it requires extremely controlled flight paths in combination with rotorcraft changes. Extension of the Hong Kong requirement to other geographical areas will require additional aircraft modifications. A detailed discussion of the acoustic requirements and the means by which they can be met by rotorcraft is provided in a Section 5.1 of this investigation.

2.3 Safety Concerns
The general public's fear of flying in rotorcraft has been well documented, most recently in Reference 3. This fear has been compounded by specific incidents such as the Sikorsky S-61 crash on top of the Pan Am building in NY, media footage of helicopter losses in various wars and the lack of information in general regarding the operation of rotorcraft. Since heliports can, in theory, be located in close proximity to inhabited areas, the safety concerns have a direct influence on public decisions regarding heliport placement. Insurance requirements have also
had an influence on the building and location of new heliports. With the exception of the Japanese heliport building spree of the late 1980’s, new heliport construction remains at a very low rate in most parts of the world. New construction can take the better part of a decade, due to zoning regulations, public hearings, environmental impact studies and the like. The cost of the construction process can be quite large. An example can be found in our nation’s capitol. Washington D.C. does not have a public heliport (other than the White House lawn). A study in April of this year (Reference 17) concluded that a small public heliport to serve the Washington D.C. area would require an investment of between $4 and $5 million to complete. Somewhat larger "vertiports" (Reference 18) capable of handling the evolving generation of tilt rotor aircraft have been estimated to cost $30 million. Construction costs of this magnitude, in combination with the operational costs and the previously described safety and noise concerns ensure that the construction rate will not substantially increase in the near future.

2.4 Costs
The general architecture of rotorcraft results in a larger number of continuously moving components than in fixed wing aircraft. These components are also exposed to higher levels of vibration than that of fixed wing aircraft. This in turn results in higher failure rates and maintenance costs. The current direct operating cost of operating a modern, medium size civil helicopter is $800-$1100/hour. This compares with approximately $400/hour for a comparable fixed wing aircraft. A rotorcraft operator must have considerably higher assets and/or charge higher prices to customers. Both requirements reduce the potential rotorcraft sales population, especially if there are sufficient conventional airports in the geographical region the buyer wishes to operate in. In addition, rotorcraft prices in general have increased at a rate significantly greater than inflation as seen in Figure 2 (Reference 19). Where at one time these aircraft were looked upon as relatively affordable alternatives to small business jets for short radius operation, current pricing forces potential buyers to scrutinize the 6-10 passenger class of vehicles more closely.
2.5 Surplus Rotorcraft
In recent years the US government has decided to release Viet Nam era surplus helicopters to the public. In some instances the vehicles were donated to local police and fire departments (Reference 20), and in some cases auctions have been the venue for distribution. The total number of aircraft dispersed in the 1992 to 1996 time frame has exceeded 1700. This compares to an annual sales rate of 300 per year for commercial and utility rotorcraft during that time. The impact on helicopter sales in this time period was considerable, and significantly changed the business climate for producers. Although it can be argued that some of the new operators of these surplus aircraft could not have afforded to buy new vehicles, a large percentage of the new users (some estimates run a high as 50%) were lost new sales. There is no reason to expect a similar release of this quantity of aircraft in the near future, but as the Army's current fleet of UH-60's ages, it is possible that a release of medium rotorcraft could significantly affect the industry again in 15 to 20 years. The impact on the small total market of such a large influx of aircraft could be devastating, particularly if new aircraft sales are poor at that future date.

2.6 Commuter Aircraft
The advent of a new class of turboprop commuter aircraft brought about by the institution of hub and spoke route systems by the airlines in the 1980's has influenced rotorcraft sales and development in several ways. First, the turboprop commuter aircraft themselves have performance capabilities which overlap some existing and potential rotorcraft (Figure 3). For a 450 mile round trip as shown, the turboprop (and the tiltrotor) designs show a significant cost advantage for any speed greater than approximately 170 knots. Although this class of fixed wing aircraft does not have vertical takeoff and landing capabilities, they can use the speed advantage and the existing infrastructure of airports and ground transportation to approximate the door to
door times, at least on longer routes, that have been the hallmark of the rotorcraft “advantage” for many years. The inherent mechanical simplicity of these commuter aircraft when compared to rotorcraft also makes it possible to provide a higher capacity aircraft for fewer maintenance and total dollars.

![Efficiency Comparison](image)

**Figure 3**

2.7 Insurance and Liability
The requirement to insure rotorcraft results in a further disadvantage relative to other means of transportation. Basic premiums are higher per seat than fixed wing aircraft due to higher actuarial losses. As with all aircraft, in the event of a loss, litigation is just as likely against the manufacturer as the operator. The result has been a underlying reluctance on the part of some manufacturers to fully support the commercial market with new products. This failure has forced continuation of older designs which do not have the additional capabilities that a new design could incorporate.

Despite this less-than-rosy list of potential issues, the world’s leading rotorcraft manufacturers have released approximately 15 new commercial designs in the last 10 years. And commercial sales have been projected to increase for the industry as a whole (Figure 1), at least over the next 5 years.

2.8 Research Trends
As the helicopter has been developed, research areas have focused on several shortcomings inherent in the dominant configuration, such as anti-torque system design, hover capability and control system development, among others. For this study of aircraft efficiency, three main parameters are of interest. The first is aircraft payload-range. This parameter is a measure of the load (payload) the aircraft can carry over a certain distance or range. Figure 4 shows an example
of a payload range curve for a generic medium weight aircraft. Payload-range capability increases require rotor lift to drag ratio improvements, parasite drag reduction, empty weight reduction, and/or engine efficiency improvements. Each of these areas have been subjects of intense research and development efforts over the years. As a result, the payload-range parameter has followed the trend shown in Figure 5. Cost is another area where large amounts of R&D effort have been expended to reduce the life cycle costs of aircraft in general, and rotorcraft in particular. These include the basic cost of the vehicle, maintenance costs and O&S (Operation and Support) costs. The final parameter that is of interest is weight. As mentioned above, weight is a key factor in improving aircraft efficiency, and it is also directly related to cost (Figure 6).
Cost As a Function Of Gross Weight For Multi-engine Helicopters

![Graph showing the relationship between cost and gross weight.](image)

Figure 6

### 2.9 Regulations

Historically, commercial aircraft regulations have been focused on safety or noise concerns. The first government safety regulations were implemented by the FAA to set standards for commercial aircraft. The first noise regulations dealt with flight corridors to minimize the acoustic footprint of departing and arriving airliners, and were implemented in the 1970's by the FAA. Specific regulations dealing with aircraft and airport acoustic emissions were first implemented by FAR (Federal Aviation Regulation) Parts 36, 91, and 150, and have been updated several times.

Rotorcraft noise regulations started in the same time frame. There are several means of reducing the acoustic signature of rotorcraft, depending on the frequency of the signature, its radius of influence, and whether the rotorcraft in question is a completely new or a derivative design. Table 1 provides possible means of reducing acoustic signature, along with impacts to other attributes connected with this study for various projected levels of acoustic regulations.
<table>
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<th>Regulation Level</th>
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<th>Delta Payload Range</th>
<th>Delta Weight</th>
<th>Delta Cost</th>
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<tr>
<td>FAR Part 36</td>
<td></td>
<td>NA: Baseline Design</td>
<td>NA</td>
<td>NA</td>
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<tr>
<td>Current (98.3 EPNL dB)</td>
<td></td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>-3 dB</td>
<td>Alternate main rotor blade tip designs</td>
<td>0</td>
<td>+8 lbs</td>
<td>+$14,500</td>
</tr>
<tr>
<td>-6 dB</td>
<td>Advanced tip designs for main and tail rotor blades, modified blade spacing for anti-torque system, main and tail rotor rotational speed reductions</td>
<td>-2% (-6000 lb n. mi.)</td>
<td>+36 lbs</td>
<td>+$26,400</td>
</tr>
<tr>
<td>-9 dB</td>
<td>Additional rotor blades, new airfoils and tip designs minimum rotor blade rotational speeds</td>
<td>-1.5%</td>
<td>+86 lbs</td>
<td>+$50,900</td>
</tr>
<tr>
<td>-12 dB</td>
<td>Alternate anti-torque system, mufflers for subsystems, variable rotor speed, active rotor blade pitch control</td>
<td>-3%</td>
<td>+200 lbs</td>
<td>+$250,000</td>
</tr>
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Table 1 - Potential Rotorcraft Acoustic Regulation Options and Engineering Solutions

Aircraft engine exhaust emissions have recently begun to be regulated, as well. Both gas turbine and piston engines have been the subject of the new legislation. For this study, we will look at gas turbine engines only, since these are the engines of choice for all but the smallest rotorcraft. FAR Part 34 (Reference 21) for turbine engine powered aircraft stipulates limits for nitrous oxides (NOX), carbon monoxide (CO), and hydrocarbons (HC) as well as smoke levels (SN). New designs from the engine manufacturers have incorporated these limits into the initial design parameters since the implementation of the regulations. To date, these modifications have had a negligible effect on engine performance (horsepower, fuel economy, and longevity). However, there is significant pressure to reduce exhaust gas emissions further, and these reductions will require changes that are projected to impact other attributes.

Automobile emissions regulations have attempted to reduce automobile exhaust emissions since 1967. The current regulated levels for NOX, CO, and HC are 1.4, 3.9, and 2%, respectively, of the uncontrolled value present in 1967 (Reference 22). Table 2 provides potential changes required to gas turbine engines and their impacts to the other attributes of interest, for varying levels of exhaust emission controls. The maximum reduction level has been chosen to approximate the current value for automobiles, where between 95 and 100% reductions have been achieved.

The ultimate emission control solution, use of an alternate fuel, is also included in Table 2. Several hydrogen-fueled aircraft studies have been completed in recent years (Reference 23)
that indicate the viability of an alternate fuel source such as hydrogen, given some significant infrastructure changes to allow production, transportation, and distribution. A detailed study of alternate fuels is beyond the scope of this thesis. However, the structure of the model lends itself to input of corrected primary parameters that reflect the alternate fuel impacts, which can then be used to investigate any changes in the behavior of the Unit Sales variable.

<table>
<thead>
<tr>
<th>Regulation Level</th>
<th>Exhaust Component Values</th>
<th>Aircraft or Engine Components Modified or Replaced</th>
<th>Delta Payload Range</th>
<th>Delta Wt</th>
<th>Delta Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>None: Current Requirement For Turbine Engines &lt;1000 kW (1341 SHP) Power Level</td>
<td>No current requirement</td>
<td>NA: Baseline Design</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>Level for Current Turbopfans (airliners)</td>
<td>SN = 187(rO)-0.168 HC = 19.6 gms/kilonewton rO CO = 118 gms/kilonewton rO NOx= (40+2(rPR)) gms/kilonewton rO</td>
<td>Fuel additives, small cycle temp changes, fuel control technology</td>
<td>0</td>
<td>0</td>
<td>+$3,000</td>
</tr>
<tr>
<td>Level for Turbopfans after December 31, 1999</td>
<td>SN = 187(rO)-0.168 HC = 19.6 gms/kilonewton rO CO = 118 gms/kilonewton rO NOx= (32+1.6(rPR)) gms/kilonewton rO</td>
<td>Large operating cycle changes (temperature, rpm, mixture), ceramic fiber reinforcement, DLE</td>
<td>+20% (+60000 lb n.mi.)</td>
<td>0</td>
<td>+$12,500</td>
</tr>
<tr>
<td>Equivalent to Automobile Emissions Level</td>
<td>1-2% of uncontrolled levels</td>
<td>Alternative fuels and/or power sources</td>
<td>-20% (-60,000 lb n.mi.)</td>
<td>1500 lbs</td>
<td>$400,000</td>
</tr>
</tbody>
</table>

Table 2 - Potential Rotorcraft Exhaust Gas Emissions Regulation Options and Engineering Solutions

Fuel economy regulations have not been imposed on the aircraft industry at the time of this study. The current availability of fuel, reflected in the lowest adjusted price in decades, does not point to new regulations being imposed any time soon. But as those of us who witnessed the fuel crises of the 1970's know, this can change overnight. For this reason, Table 3 provides the impact to the primary parameters of various solutions to potential fuel economy regulations.

19
<table>
<thead>
<tr>
<th>Regulation Level</th>
<th>Components Modified or Replaced</th>
<th>Delta Payload Range</th>
<th>Delta Weight</th>
<th>Delta Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Current</td>
<td>NA: Baseline Design</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>+10%</td>
<td>Parasite drag cleanup, rotor/engine speed adjustments, fuel control technology</td>
<td>+30,000 lb n. mi.</td>
<td>+10 lbs</td>
<td>+$4,000</td>
</tr>
<tr>
<td>+25%</td>
<td>Parasite drag reduction, higher BTU fuels, new rotor blade, revised or new engine cycle, substantial weight reduction</td>
<td>+75,000 lb n. mi.</td>
<td>-500 lbs</td>
<td>+$200,000</td>
</tr>
<tr>
<td>+100%</td>
<td>New design concept (tilt rotor, tilt wing)</td>
<td>+300,000 lb n. mi.</td>
<td>+1000 lbs</td>
<td>+$4,000,000</td>
</tr>
</tbody>
</table>

Table 3 - Potential Rotorcraft Fuel Economy Regulation Options and Engineering Solutions

The maximum improvements listed mirror those of the CAFE (Corporate Average Fuel Economy) standards used in the automobile industry. These regulations have already doubled the automobile fleet fuel economy from unregulated levels (Reference 24). The aircraft solutions presented in Table 3 include both propulsion system improvements and general aircraft efficiency improvements. The same improvements that help payload range by definition improve fuel economy.

The three regulations investigated here, noise, exhaust emissions, and fuel economy, have been imposed on automobiles over the past three decades. Basic safety and exhaust emissions regulations first were imposed in 1968. Fuel economy regulations were not imposed until 1975. Unfortunately, the technical differences between automobiles and helicopters prevent using the sales trends seen in the automobile industry as benchmarks for behavior in the rotorcraft industry. The differences between gas turbine and piston engines result in somewhat different solutions to exhaust emissions and fuel economy. External noise reductions in automobiles are almost solely achieved by the use of parasitic devices, such as mufflers. Although rotorcraft could, and in some cases do use a type of muffler or other exhaust pipe device to meet acoustic requirements for engine noise emissions, the noise emanating from the rotor systems must be treated in completely different ways. The rotor changes may involve variations in the blade pitch, rotational rpm, blade thickness, and relative position of the rotor and fuselage, among others. These alternatives are completely unnecessary for automobiles, since the primary propulsive interaction with the environment is through the tires, not a rotor. Tire tread patterns do affect the external acoustic signature of vehicles, as anyone who has passed a truck or car with snow tires on the highway knows, and recently have been required to meet specific external noise standards. Of course, a rotorcraft does not have this tire problem.
While exhaust emissions are usually treated by combinations of operating cycle temperature for both types of engines, the differences between the thermodynamic cycles of the car’s piston engine and the rotorcraft’s turbine engines prevent relatively simple but heavy solutions, such as the catalytic converter, to be easily accommodated to for use on aircraft. To date, aircraft emissions have been improved by judicious adjustment of turbine temperatures, airflow and strict control of the combustion process by digital fuel control systems.

Fuel economy is one area where rotorcraft improvements do have some similarity to automobile industry experience. Improvements in engine efficiency, reductions in drive system frictional losses, electrical losses, and parasite drag can and have been used in both instances to improve fuel economy. Rotor performance improvements, however, are not on the automobile parts list. In general, automotive experience is not applicable to the problem investigated here, although the model described in the following sections could be adapted to specific automotive parameters without much difficulty.

3.0 Model Description
Model development was initiated with a series of meetings with the original client, the Director of Technical Engineering at a major helicopter company. Discussions with the principal client generated the initial problem statement, variable list, and reference modes shown in Figures 7, 8 and 9, respectively. The problem statement (Figure 7) was deceptively straightforward. As the client company moved into the commercial marketplace, the hope was that increased aircraft efficiency (as compared to the competition) would provide a competitive advantage that would result in increased sales volume. The client feared that sales could decline from a combination of lack of competitive product, an inability to deal with government imposed regulations as well as with the competition, and a research investment plan not focused on the correct target technologies, or of adequate size. This fear was present even in light of the sales trends forecast for the industry (previously described in Figure 1).
Problem Statement

• We would like to determine the impact on sales of improved payload/range capability.

• We want to find out which regulations have the largest impact on sales, and which would lend themselves to research investment to change their impact on sales and gain competitive advantage?

![Graph showing Sales over time from 1999 to 2010 with Hope and Fear curves.](image)

This basic problem statement was used to create the variable list in Figure 8. The variable list can be categorized into three broad categories: financial/business, technical, and social (corporate structure). Variables focusing on the financial and business issues of this problem included sales, revenues, time to market, opportunity cost, market share, cash flow, business plan fit, investment, annual savings, strategic initiative fit, payback period, and ROI. Variables with a technical focus included payload range, weight, level of technical risk, competitive advantage, technology mix, reliability and safety. The social structure-related variables included the size and makeup of the workforce, degree of co-location of the project staff, the age variation and learning capabilities of that staff, cultural differences, and the means of interfacing with non-co-located groups.
After further discussion with the client, these variables were pared down to six reference modes which are sketched in Figure 9. The Sales reference mode is the basic problem statement - the hope (1) is that sales will increase with time, while the fear (2) is that the company will be out of business within a relatively short time span. For this model, the time horizon chosen was 10 years. This value was based on the experience of the client and the author as to how long the company might be able to sustain continuously decreasing sales.
The Payload/Range reference mode assumes that the existing research activities in materials, propulsion systems, aerodynamics, and fuel development will yield increased payload-range capability as a matter of course. The desire is to have this increase in efficiency outstrip the competition and provide a discriminator for additional sales.

The Weight reference mode is particularly important, since for rotorcraft (and aircraft in general) weight is an indicator of potential performance, and can be directly correlated to cost. As aircraft are designed to include added features desired by the customer, or are affected by regulations and requirements not originally part of their specification, weight grows. Reducing the rate of increase of weight can provide a cost and performance (efficiency) advantage.

As Time to Market decreases, it is hoped that competitive advantage and sales will increase. So this reference mode could provide a measure of any sensitivity to a time window which must be met to maintain a competitive advantage. The Competitive Advantage reference mode has the inverse trend to the Time to Market mode; as time passes, we would like our competitive advantage to increase; the fear is that it will erode, taking Sales along the same path.

The last reference mode, Technical Risk, shows the desire to have technical risk decrease as sales grow. Reduced risk means fewer failed research projects, consistent competitive advantage increases due to successful projects, and lower costs in the long run.

Following the System Dynamics standard method as described in Reference 25, momentum policies were then listed to support (or degrade) these reference modes. The momentum policies are provided in Figure 10, and are the immediate responses to the reference modes if the client did not have a System Dynamics model to provide different insights into the problem.
Rotorcraft Efficiency: Momentum Policies

- Advance technology development to improve efficiency (payload/range).

- Improve time to market while maintaining the quality and level of technology development.

- Maintain an informed technology development team large enough to satisfy demand.

- Anticipate and participate in changes in regulations to reduce any negative impact on efficiency.

Figure 10

The first policy was aimed at improving efficiency (payload-range) to try to follow the upper line in the reference mode chart. This policy, along with the second policy, are the basic premise of the problem statement. The second momentum policy would reduce time to market without affecting the quality or level of technology development, which in turn would provide benefits in competitive advantage and sales. The technology development team can perform to expectations only if it receives timely, correct information, and if it is large enough to produce useful new technologies. This is the third policy. The last momentum policy is meant to weaken the negative loop affecting efficiency. This loop is presumed to result from unanticipated and/or inordinately stringent regulations.

The System Dynamics model used in this study is based upon three hypotheses. The first hypothesis, shown in causal loop form in Figure 11, is a more detailed restatement of the original problem statement. Starting from "Sales" in the lower left, as Sales increase, Economies of Scale improve Profits and increase the Money Available for Technology Improvement. This money can be used in two ways, according to this hypothesis. First, it can be used to fund Technology Improvements, which would increase Payload/range capability, reduce Weight, and reduce Cost. These changes would improve our Competitive Advantage, resulting in increased Sales. This is a positive, or reinforcing loop.
**Hypothesis 1**

Improving efficiency will improve our competitive advantage and increase sales. Regulations which reduce efficiency will degrade our competitive advantage and reduce sales.

The other path in this hypothesis assumes that if Money Available for Technology Improvement increases, regulatory agencies would take this as a signal that companies could afford to research and develop technologies to meet more stringent regulations. The agencies would increase Regulation Imposition, which would cause negative changes in the three performance measurement attributes: Payload/range, Weight, and Cost. (Payload/range would decrease, Weight would increase, and Cost would increase). These changes would reduce Competitive Advantage, decreasing Sales, reducing Profit, and reducing the Money Available for Technology Improvement. This would signal the regulatory agencies to stop new Regulation Imposition. This loop is a negative or balancing loop.

The second hypothesis, shown in Figure 12, assumes the same basic positive loop as the first hypothesis. As more Technology Improvements are available, Payload/range increases and the improved Competitive Advantage increases Sales. This generates additional Profit, providing more Money Available for Technology Improvements, increasing the number of Technology Improvements which in turn increases Payload/Range. The negative or restoring loop for this hypothesis starts with the increase in Competitive Advantage as Payload/Range increases. This increase in Competitive Advantage reduces Market Pressure to Improve Technology, since the
product already has a competitive advantage and increased market share. However, this reduced Market Pressure to Improve Technology also decreases the Level of Technology Risk for the technology improvements to be implemented. This in turn reduces Payload/Range. Available Time to Market influences the Level of Technology Risk, as well. Shorter Available Time to Market also reduces the Technology Risk level that can be implemented, so improvements in Payload/Range will be reduced relative to longer Available Times to Market.

**Hypothesis 2**

*Low risk technologies for immediate application to product may not provide the level of improvement the market demands and competitors may provide. So sales can suffer even as you’re shortening time to market.*

![Figure 12](image_url)

The third hypothesis, shown in Figure 13, again assumes the same basic positive loop for Technology Improvements increasing Competitive Advantage, Profits, and Money for Technology Improvements. In this hypothesis, the increase in Money Available for Technology Improvement increases the number of people who can work on technology improvements. An increase in the Number of People reduces the time needed to complete the project, reducing Time to Market and improving Competitive Advantage. At the same time, an increase in the Number of People will reduce the general Experience Level of the workers, reducing their average productivity and increasing the Time to Complete the Project. This acts as a restoring loop. The last part of this hypothesis assumes that as the Number of People on a project increases, the Degree of Co-
location increases, as well. This increases the amount of Information Available, which improves our Competitive Advantage.

Hypothesis 3

A technology development team has to be the right size and have sufficient funding to be able to produce technology advancements demanded by the customer or the competition. The team must have enough correct information regarding regulations and the competition’s research direction in order to succeed.

The causal loops representing these three hypotheses were then modeled in Vensim (Reference 27) using a combination of the molecules of structure (Reference 26), modified molecules of structure from the same reference, structure from the product development model (Reference 28), new structure, and existing or projected information regarding the interaction of key variables. For the first hypothesis, four structural components were used to model the first loops. The product development model (Reference 28) was modified to model the Technology Improvement portion of the loop. This section (Figure 14) also included generation of the Technology Impacts on Weight, Cost and Payload/Range, and included replenishment of potential technology improvements through new creation of projects in the Technology Base.
The Regulation Impacts on Payload/Range, Weight, and Cost were modeled by a significantly modified product development model as shown in Figure 15. The combination of Technology and Regulation Impacts on the three primary attributes (Payload/range, Weight, and Cost) were combined to produce the "Actual" attributes as input to the model section shown in Figure 16. This section uses Product Attractiveness and Market Share molecules (Reference 26) appropriately modified to include lookup functions for the Effects of Weight, Cost, and Payload/range on the Attractiveness of the product.
The last section of the loop, which included Sales, Revenues and Money Available for Technology Improvements, was modeled as a new structure based on conversations with Professor Jim Hines. This structure is shown in Figure 17. A schematic of the combined structure for the first hypothesis' loop is shown in Figure 18.

Hypothesis 1 Model Schematic

![Diagram of Hypothesis 1 Model Schematic]
Figure 19 provides the section of the model that describes the second hypothesis. This section uses the Protected Sea Anchor Pricing molecule (Reference 26) modified to model the level of Technological Risk as Market Pressure to Improve Technology and Available Time to Market changes. Figure 20 incorporates the second hypothesis structure with that of the first hypothesis schematic (Figure 18).

**Model Schematic**

**Hypothesis 1 + Hypothesis 2**
The structure for the third hypothesis is shown in Figure 21, 22 and 23. It consists of three molecules from Reference 26, appropriately modified. The first molecule (Figure 21) is the Aging Chain with Productivity. This structure models the behavior as the number of people grows and the experience level mix changes, affecting average productivity and project completion rates. Another aging chain, without productivity effects, is used to represent the Information Available as a result of co-location as the Workforce grows (Figure 22). As the information ages, the probability of the information being correct grows. This Correct Information is used as an input to a modified Protected Sea Anchor Pricing molecule shown in Figure 23.
Figure 22

Figure 23
The completed model is presented in schematic form in Figure 24. Early in the process, client preferences indicated that flexibility was a key attribute to incorporate in the model if it was to be useful over the time period of interest. The trends of technology improvement, hiring, regulation generation, dollars spent on technology improvements, etc. were parameters that were subject to individual interpretation as well as modification with time. Because of the desire for flexibility, several of these items are modeled as constants or lookup tables, so as to easily incorporate changes due to structure variations in the future. The flexibility request was also accompanied by questions regarding correlation of specific parameters, and the model’s capability to predict future sales values, rather than just trends of behavior.

The general suggestion that the model was to be capable of real number predictions was to be a recurring problem throughout this study. The client’s point of view was that models not capable of specific value correlation and predictions were to be looked at with skepticism. The author, who has modeling experience not related to System Dynamics, also confronted some instances where the prior experience left questions regarding the results of the Systems Dynamics modeling. However, the insights provided by the model turned out to be relatively independent of the specific values used for the trends mentioned above (especially within the ranges described). This result indicated the basic robustness of the model’s structure and resulting behavior, and was a key factor in gaining further acceptance of the methodology by both the client and the author.
4.0 Sensitivity Studies

A series of sensitivity studies were performed as a first step to understanding the interactions of the completed model. The initial series of sensitivity studies were performed by varying the components of the model structure in Figure 14. In this case, the Technology Impact on Payload/range, Weight and Cost were varied to determine the effect on the primary variable, Unit Sales, and to discover any other insights which might be forthcoming due to the dynamics of the model. The Technology Impacts were doubled and halved relative to their baseline values. The results of these changes is shown in the causal traces presented in Figures 25, 26, and 27, below. As each Technology Impact parameter is varied (lower or third row of charts), the variable does show improvements commensurate with the multiplying factor used. For each case, the01 is the baseline, the second trace is for the Technology Impact value doubled (the02, 04, and 06 respectively for PayloadRange, Weight, and Cost), and the third set of lines represents halving the baseline technology improvements (the03, 05, and 07).

The second row of charts shows the Regulation Impact on PayloadRange, Weight, and Cost. The variation in Technology Improvements show little or no influence on this parameter, but the total magnitude of the Regulation Impact does affect results in the Actual PayloadRange, Weight, or Cost of the top row of plots. In general, the variation in Actual PayloadRange, Weight, and Cost vary within +/-20 to 25% of the baseline value, despite Technology Impacts varying from -50% to
+200%. The impact of the variations in the Actual parameters on Sales is presented in Figures 28, 29, and 30 below. Sales varies up to +6% from the baseline for the Payload Range case (Figure 28), which is significant. Note that the impact of Technology Improvements on Weight and Cost produce a similar impact on Sales. Because of the close relationship between weight and cost for aircraft, this is not surprising. The combination of Cost and Weight produces variations very similar to that of Payload Range alone. The final result at the end of the time period in question, a 20% reduction in aircraft sold per month, requires further analysis to determine alternatives to the structure that caused this behavior.

Since technology improvements act as part of the positive loop diluting the impact of regulations, it is worthwhile investigating the parameters that cause the three Technology Impacts' behaviors. Looking back at Figure 14, we can see that each Technology Impact parameter has three inputs: the Technology Improvement Factor, the parameter Risk Adjustment Factor, and Technology Improvements Available. We will discuss the Risk Adjustment Factors in a section below. The Technology Improvement Factors were conservatively chosen based on current experience with Technology Improvement projects in the client company. For Payload Range, an improvement of 3000 lb-nmi was assumed per project. This represents a 1% improvement per project. A 1-3% improvement in rotor L/De would be considered significant using a single technology idea and the current state of the art. Similarly, an improvement of 25 lbs for a single project, on average, is a
reasonable assumption for projects which do not involve a radical innovation. An equivalent cost improvement of $20000/project is also a readily achievable goal. For a significant R&D effort, doubling these returns would not be out of the question and would positively affect Sales.

Increasing the number of Technology Improvements Available would have a positive impact on both the Technology Impacts and on Sales. The current R&D structure of this company has specific personnel in three areas in the Technology Improvements "pipeline" of Figure 14. It turns out that the current structure can support considerably more R&D people than are currently hired. Figures 31, 32, and 33 show how doubling the number of people in the Completing R&D Workforce can increase Sales by significantly increasing the Technology Impact on PayloadRange. For each chart, the10 represents the baseline and the11 represents doubling the Completing R&D Workforce. The increase in Technology Improvements Available also increases the Technology Impact on Weight and Cost, resulting in a Sales curve that regains the initial sales rate within 4 years. The workforce increase is based solely on a hiring increase; the mix of gray hairs, rookies and experienced personnel was not changed initially.

Figure 31

Figure 32

Figure 33

Since both the number of people available in the Workforce and Average Productivity affect the Technology Improvements Available, changing the Average Productivity should have a similar effect on Sales. This can be accomplished by increasing training to reduce the time it takes to
move Rookies to Experienced, and/or slowing the Retiring rate to keep the GrayHairs in the Workforce longer (Figure 21). For the company in question, a retirement package was recently offered and enthusiastically accepted by the GrayHairs, so these results are particularly timely.

As shown in Figure 34, reducing the time it takes for Rookies to become Experienced from 24 to 6 months (the23 to the24) does not result in any significant change in Sales or Market Share. Similarly, reducing the time it takes for Experienced Personnel to Gain Wisdom has a minimal effect (the23 to the26). However, the productivity of the GrayHairs can significantly affect the Sales picture. Cutting the Retirement Rate in half (the25) improves Sales by about 10%. Doubling the Retirement Rate (the27) results in a Sales decline of 15% by the eighth year, with a significant downward trend (Figure 35). Clearly, the solution to improved sales is not retiring the most productive segment of the Workforce. Alternately, increasing the productivity of the Rookies and the Experienced personnel could help moderate a Sales decline.
Varying the PayloadRange, Weight, and Cost Risk Adjustment Factors (Figure 14) also affects the Technology Impacts on these parameters as can be seen in Figures 36 and 37. The starting Risk Adjustment Factors were chosen based on experience with technological improvements in the three areas. Of the three factors, only the PayloadRange Risk shows any interesting behavior. In this case (Figure 36) doubling the risk (the29) relative to the baseline (the28) causes a short term sales reduction, with recovery by the fourth year. Halving the risk (the30) does not, however, produce a sales increase of the same magnitude. The other risk factors show even less sensitivity. The Time Window, however, has a significant effect on Sales, as shown in Figure 37. Halving the Time Window results in more risk of failure (the35), reducing Sales considerably, until by the 100th month they have been reduced by almost 40%. Doubling the Time Window (the36) prevents the Sales decrease, but results in a leveling of Sales, not the growth we are hoping for. Since the Time Window also affects the competition’s results, the ability to develop productive technologies within a reasonable time period seems to be a key requirement.

The co-location hypothesis (Figure 13), that improved communication can be the basis for improved Competitive Advantage resulting in increased Sales, is only partially borne out by
varying parameters in that part of the model as shown in Figure 22. In Figure 38 below, increasing the co-location extent from 0.5 (the37) to 1.0 (the38) has a positive effect on Sales. This parameter change is the equivalent of having all personnel in the same building. Reducing the co-location extent to near zero (the39) reduces Sales slightly. The other parameters that contribute to the amount and maturation of information do not greatly influence Sales. Figure 39 shows the effect of doubling the Co-location Extent, the Information Generation Factor, and the General Information Collected (Figure 22), with essentially no improvement to Sales relative to the impact of the Co-Location factor alone (Figure 38).

This lack of sensitivity prompted further investigation. Reducing the Time for Info Quality to Improve by a factor of two (the42), along with increasing the Time for Obsolescence (the43) again showed little impact on Sales relative to the impact of the co-location factor alone (the38) as can be seen in Figure 40. However, as expected, the amount of Correct Information improved dramatically (Figure 41). This apparent anomaly was traced to the Competitive Advantage of Information function, which tops out if more than approximately 125 pieces of new information are
obtained each month. The function can be modified to improve "headroom" and achieve the
preconceived result, but this is undesirable for two reasons. First, it negates the original structure
assumptions for this part of the model, i.e. it forces the model behavior to match existing
information, rather than just letting the model provide the behavior associated with the structure.
Also, modifying the function would ignore the information provided by the client, which had been
based on years of experience involving co-located teams and the timeliness of information in this
industry. For these reasons, the function was not modified. The final conclusion drawn from this
exercise is that increased co-location and improvements in information quality are factors in
improving Sales for the structure modeled here, but less significant factors compared to some of
the other sensitivities we have investigated. An improvement of 6-10% of Sales can be realized if
the effects are combined.

The next set of sensitivities involve the impact of additional money available for technology
improvements. The logical place to investigate this is in Figure 17. By increasing the Fraction of
Revenues to Technology Improvement from 5% (the47) to 10% (the48), we get the results in
Figure 42. These results are not intuitive! Sales drop by over 10% as Money Available for
Technology Improvements doubles. Further investigation shows that the Technology
Improvements Well (Figure 43) is being replenished at a much higher rate than previously, but
the Technology Base itself is not increasing. We have seen this behavior previously when looking
at the sensitivities of the parameters in Figure 33. The structure of the R&D organization does not allow an increased number of improvements because of personnel restrictions in identifying, selecting, and completing R&D projects. The flat lines in Figure 44 confirm the previous findings again. But that still doesn't explain why Sales have decreased, rather than stay flat.
Part of the explanation is that the increase in the Money Available for Technology Improvements also acts as a trigger in the section of the model dealing with regulations (Figure 15). This behavior was part of Hypothesis 1. As Money Available for Technology Improvements increases, the behavior shown in Figure 45 results.

The increase in the Implemented Regulations cannot be moderated by the increase in Regulation Repeal. The resulting increase in Implemented Regulations affects Sales by increasing the negative Regulation Impacts on PayloadRange, Cost, and Weight as shown in Figures 46, 47, and 48, below, and as was described earlier in the discussion of the R&D module. The Technology Impact on these parameters show virtually no change, as would be expected since the number of Technology Improvements is constrained by the R&D structure (both personnel number and type).
Actual Payload Range

"Reg. Impact on Payload Range"

Technology Impact on Payload Range

Actual Cost

"Reg. Impact on Cost"

Technology Impact on Cost

Actual Weight

"Reg. Impact on Weight"

Technology Impact on Weight

Initial Payload Range

the47: 300,000    the48: 300,000

Initial Cost

the47: 4 M    the48: 4 M

Initial Weight

the47: 10,000    the48: 10,000
5.0 Sensitivities to Regulations

Sensitivities to parameter variations in the Regulation module (Figure 15) are the most interesting in this model. The impact of increasing Money Available for Technology Improvement has been described above. Variations in Regulation Research Results are shown in Figure 49. The increase in the new potential regulations from 10 to 20 per month, while the decreases the value to 5. The latter results in a flat Sales chart. The former results in a 30-35% reduction in sales by the 100th month. This would indicate another significant means of limiting the effect of new regulations - preventing them from entering the potential pool in the first place.

![Graphs showing Our Unit Sales, Market Share for Product, and Industry Unit Sales for different scenarios.]

A 33% increase in the Impact of Public on New Regulations results in a 7-8% reduction in Sales in the 100th month, assuming the public activity is in support of the regulation. A 33% decrease in activity results in a 7-8% improvement in Sales relative to the baseline. This last trace is fairly flat, the Sales decline seemingly arrested by the public activity's...
effects. Lobbying shows similar trending results, but of course with the opposite sign. Figure 51 shows the results of doubling and halving the Lobbying Impact on New Regulations.

Increasing the Lobbying Impact on New Regulations (the55) results in a Sales increase. To investigate the sensitivity of increasing Lobbying and Public Impact on all phases of the regulation module, two sets of runs were made. The first, Figure 52, increased lobbying by 10% (the56) and 20% (the57) relative to the baseline (the49). These results indicate that an increase in lobbying activity of approximately 25% should result in a flat Sales curve. Increasing the activity beyond those levels would result in a Sales increase. In contrast, the Public Impact figure (Figure 53) shows small changes in Sales for 10% (the58) and 20% (the59) increases in activity. This does not imply that public activity has less of an influence on regulations than lobbying. Rather, it indicates the fact that lobbying for military programs has historically been more successful for this
client. The move into the commercial marketplace may force a re-think of the relative values assigned to these two variables.

\[
\begin{array}{c|c}
\text{Our Unit Sales} & \text{Our Unit Sales} \\
20 & 20 \\
17.5 & 17.5 \\
15 & 15 \\
12.5 & 12.5 \\
10 & 10 \\
\end{array}
\]

\[
\begin{array}{c|c}
\text{Market Share for Product} & \text{Market Share for Product} \\
0.6 & 0.6 \\
0.5 & 0.5 \\
0.4 & 0.4 \\
0.3 & 0.3 \\
0.2 & 0.2 \\
\end{array}
\]

\[
\begin{array}{c|c}
\text{Time (Month)} & \text{Time (Month)} \\
0 & 0 \\
50 & 50 \\
100 & 100 \\
\end{array}
\]

\[
\begin{array}{c|c}
\text{Industry Unit Sales} & \text{Industry Unit Sales} \\
\text{the49: 40} & \text{the49: 40} \\
\text{the56: 40} & \text{the58: 40} \\
\text{the57: 40} & \text{the59: 40} \\
\end{array}
\]

**Figure 52**

**Figure 53**

### 5.1 Acoustic Regulations

Table 1 (page 18) provides a list of current and potential rotorcraft acoustic regulations. The impact of these existing and potential regulations on sales depends on the cost of meeting the new requirement(s). This cost consists of several components. First is the actual cost in dollars of implementing a solution. This includes the cost of design, tooling, manufacturing and distribution of changes required for the rotorcraft to meet the regulation. The cost of personnel required to perform this work must also be included. The implementation costs result in a reduction in available funding to do other tasks, including research to improve rotorcraft efficiency. Theoretically, this funding shift could erode market share in the long term, but only if the competition already has products that can meet the new regulations. For this study, it is assumed that the competition is in the same market situation as the client company - if a new
The required changes in the rotorcraft itself to meet the regulations potentially incur another cost - that of a performance loss to the vehicle, reducing market attractiveness and reducing sales. These costs can be quantified based on projected engineering changes required to meet the regulations. Table 1 also shows potential engineering changes expected to be required to meet a series of hypothetical acoustic regulations. As the regulations become more stringent, the engineering changes required to meet the acoustic levels become more exotic. The impacts on weight, payload range, and cost also tend to grow, although in instances where there is a significant technology leap, such as active blade control, a large improvement in performance relative to the regulation can be achieved with a reduced negative impact on the three primary parameters.

The current regulation for a 10-11000 lb. aircraft specifies a 98.3 EPNL dB sound pressure level limit for takeoff. To reduce this level by 3 dB would require changing the conventional main rotor blade planform shape to a more advanced design, such as a larger swept and tapered tip. It may be necessary to add anhedral to the tip design (bending the tip downward), depending on the blade thickness of the baseline design. The change in tip design would have a negligible impact on payload range. The impact on weight would be on the order of 8 lbs for a four bladed rotor system. A change of this magnitude would require a new rotor blade design and a set of new blades themselves. The cost of a new design has been estimated at $1,000,000 spread over a 400 aircraft production run. This, in combination with the cost of a blade set, results in the $14,500 estimated cost per aircraft shown.

For a 6 dB reduction in noise, more serious measures have to be taken. In addition to a more advanced tip design, the anti-torque system (tail rotor) would have to be modified, and the rotational speed of both rotor systems would be reduced. The anti-torque system modifications would include blade tip modifications to the tail rotor, and the incorporation of unequal spacing of the blades around the tail rotor hub. The rotor speed reductions show up as increased torque requirements for the gearboxes, increasing the gear face widths and bearing sizes to maintain the life expectancies of the components. These changes increase the weight of the gearbox. The combined impacts of these changes are shown in the table. A 2% reduction in payload range (primarily due to the weight impact) is projected, as is an additional 28 lb weight increase over the -3dB case, for a total of 36 lbs. The cost increment is based on the additional tail rotor and gearbox changes, and result in almost doubling the cost seen in the -3dB case.
For a 9 dB reduction in noise, total redesigns of the rotor systems are needed. This requires new airfoils and a next generation tip design which in turn adds a $3 million powered model wind tunnel test to the total bill. Meeting this level of noise requires additional blade area. This is most easily met by increasing the number of rotor blades, which will require a new hub design. The total bill is estimated at $50,900 per aircraft if these costs are spread over a production run of 400 aircraft. The larger weight impact (86 lbs vs. 36 lbs for the -6 dB case) is somewhat offset by the improved performance of the new airfoils on the rotor system and the improved aspect ratio of the larger number of blades. The end result is a reduction in payload range of 1.5% rather than the 2% reduction predicted for the -6dB case.

A 12 dB reduction would require a new type of anti-torque system aimed at reducing noise, such as a buried fan design. Electronic controls for varying rotor rotational speeds and blade pitch around the azimuth would also be needed. Individual subsystems would be required to have their own muffler systems. The total impact on payload range, weight and cost are estimated to be -3%, +200 lbs, and $250,000, respectively.

The impact on Sales is shown in Figure 54 for the three cases of increased acoustic regulation.

Figure 54 Acoustic Regulations Sensitivities
The first column of charts in Figure 54 show the impact on Sales of the -3dB (the61) and -6dB (the64) cases described above. As can be seen from the traces, neither regulation level shows a significant difference from the baseline (the60). The second column shows the impact of the -9 dB noise reduction level (the68) and the -12 dB level (the69), again compared to the baseline (the60). In this case, the68 (-9dB case) shows a 1% reduction in Sales relative to the baseline. The69 shows approximately a 2.5% reduction at the worst point. This stunning lack of sensitivity coerced the author into running a case where all of the impacts of the -12dB case were doubled. This is shown in the right hand column of Figure 54. The 6-7% reduction in Sales is a logical extrapolation (and sanity check) of the 2-3% reduction of the69. The small impacts on key parameters required to meet these acoustic levels indicate that research money may be better spent elsewhere in the search for greater sales.

5.2 Exhaust Gas Emission Control Regulations

Aircraft emission control regulations are in their infancy, especially when compared to the work that has been accomplished in the automotive industry. While automobile exhaust emissions regulations were first imposed in earnest in 1968, the first aircraft emissions regulations were not implemented until 1984. For the aircraft industry, these regulations are a first step in what promises to be a broader implementation of regulations aimed at combating production of greenhouse gasses, which have been indicted as a causal factor in global warming. Since aircraft in general, and commercial airliners in particular, tend to deposit their exhaust gasses in an environment that is much closer to the one that is being protected by the regulations, it is curious that these regulations have not been implemented sooner. Two factors have contributed to this delay. First, performing research at altitude has been difficult. The availability of research aircraft capable of performing measurements at altitude, and reductions in NASA's research budget have hampered the data collection required to create these regulations. Secondly, aircraft safety issues have, as always, been paramount in the eyes of the regulating agencies. Funding has been directed toward the highly visible safety issues, while the environmental issues, which are perceived as very long term, have been put on the back burner. Also, the specific aircraft changes required to meet emission regulations could themselves impact aircraft reliability and potentially, safety. However, the adoption of the regulations by the ICAO has now prompted a general interest in such regulations and more stringent requirements can be expected in the future.

Table 2 (page 19) provides a listing of the potential aircraft emission regulations which could affect rotorcraft. The table also provides the potential engineering changes required to meet
varying levels of emission controls, along with their impact on the three metrics used here, payload range, weight, and cost. The solutions can be broken down into three categories: the improvements that are confined to the engine itself; those that include both engine and airframe impacts; and those that include airframe, engine, and infrastructure. Aircraft are considerably different than automobiles in that the propulsion systems are provided by an outside supplier as a unit to be installed in the airframe. So initial emission improvements will most likely be the engine manufacturer's responsibility. Small changes in cycle temperatures, airflow mixing and the like should be capable of meeting the first level of regulations.

As the regulations become more stringent, the engine modifications will become more advanced technologically, and may require help from the airframe interface. In automobiles, that interface became the exhaust system’s catalytic converter. It is entirely conceivable that devices such as the catalytic converter might be developed to meet the more stringent regulations. These devices could require space and weight allocations on the part of the airframe manufacturer, which in turn will affect payload range, weight, and cost. At the far end of the spectrum, the most stringent regulations may require new fuel sources for existing propulsion systems, or new propulsion systems entirely. A new fuel source, such as hydrogen, would require a re-think of airframe real estate to be able to accommodate a cryogenic fuel tank and other attendant equipment. New propulsion sources, such as fuel cells, will require a broader change in system architecture. For both of these cases, projections from several expert studies (Reference 23) have been used to estimate the impact on our three metrics.

Since helicopters in this weight class do not currently have to meet emission requirements, even an increase to the level currently met by airliners has an impact. Engine cycle changes, primarily focused on temperature in the combustion process, fuel additives to increase oxygenation, and more precise control of the combustion process by a full authority digital electronic fuel control (FADEC) can meet these levels with a small estimated impact in cost ($3,000 per aircraft). More stringent emission controls require additional changes.

Airliner turbofan engines will be required to meet a more stringent level of control after December 31, 1999. A helicopter turboshaft engine attempting to meet the new level of emissions control would require additional operating cycle changes (temperature, operating rpm, pressure ratio) in addition to one or both of the new technologies listed in Table 2. The first, ceramic fiber reinforcement of the turbine blades will allow significantly higher combustion temperatures (Reference 29) to reduce emissions and improve engine performance. The second option is DLE or Dry Low-Emission combustion (Reference 30) which utilizes a fuel staging system in combination with strict temperature control to limit emissions. A combination of the two has been
assumed for the table, with a 20% increase in payload range, zero weight, and $12,500 cost impact.

It is interesting to see the types of changes that would probably be required to meet the same level of emission controls that automobiles are currently required to meet. This level, 1-2% of the uncontrolled levels, would almost certainly required an alternate fuel or power source. In this projection, payload range has been estimated to decrease 20% from the baseline due to the large weight delta associated with cryogenic tanks required for hydrogen fuel. A weight penalty of 1500 lbs (15% of baseline takeoff gross weight) has been assessed, as has a 10% of baseline cost penalty.

The impact on Sales of the emission control options of Table 2 are presented in Figure 55.

![Graph showing market share and unit sales over time for different product options.](image-url)
The initial level of exhaust emission regulation, that currently used on airliners with turbofan engines, produces no measurable impact on Sales, as can be seen in comparing the baseline to the level which will be imposed on airliners after December 31, 1999. As can be seen in Figure 55, this level produces an increase in Sales of as much as 5%; not an expected result! The reason for the increase in Sales can be seen in Table 2. The method used to meet this requirement improves engine efficiency for both exhaust cleanliness and fuel usage significantly. This improves payload range, overcoming the losses in Sales due to the increased costs of the modification. The same is not true for the most stringent exhaust emissions regulation, as seen in the74. Here significant impacts to all three of the measured parameters conspire to produce a 20% loss in Sales relative to the baseline.

5.3 Fuel Economy Regulations

The fuel economy regulations currently imposed on automobiles in the United States resulted from the fuel crises of 1973 and 1979. Although prices of aircraft fuel significantly increased at the time, the aviation fuels were never in short supply. In the future, it is entirely possible that a resurgence of the OPEC cartel, or the depletion of fossil fuel reserves in general, could cause the imposition of fuel economy regulations on all vehicles. For automobiles, the regulations were met by using smaller, more efficient engines, lighter weight structures, reducing aerodynamic drag, and reducing drivetrain and electrical power losses. Similar engineering solutions could be applied to rotorcraft if such regulations came to be in the future. For aircraft, these engineering solutions would also be the same as those required to improve payload range capability. These would include more efficient engines, lighter weight, reduced drivetrain, hydraulic, pneumatic, and electrical power losses, and improved aerodynamic efficiency (L/D).

Combinations of these solutions were used to complete Table 3, for varying levels of potential fuel economy regulations. Since fuel economy regulations for aircraft do not currently exist, the levels were chosen as percentages of current aircraft levels. The levels range from easily accomplished to extremely exotic. In fact, the most stringent level has been projected to be met with an entirely new design concept, in this case the tilt rotor, to achieve the 100% increase in range listed.

The first level, a 10% increase in economy, can be painlessly met by a combination of existing technologies. Parasite drag cleanups and rotor/engine speed adjustments are relatively inexpensive and easy to do. Since most aircraft now have some form of FADEC, the rotor speed and operating level changes are easy to accomplish. A small weight impact has been assessed
for the drag cleanup, since changes to components (fairings and the like) will most likely result in sub-optimum design solutions for weight. The cost impact has been estimated for a small development program for the items listed.

The 25% increase in fuel economy would require more significant changes, including a new main rotor blade, significant drag reduction (rather than just the cleanup of the 10% case), substantial weight reduction and further engine/fuel tweaks. The new rotor blade requires the wind tunnel testing mentioned previously. The weight reduction can be extremely costly, since most aircraft are already designed with minimum weight as a primary design driver. Finding an additional 5% of the takeoff weight for elimination requires clever redesign, new materials, and occasionally new design standards. The $200,000 value represents a best estimate based on the existing and projected state of the art with regard to materials technologies, stress analysis and manufacturing techniques.

The 100% increase in fuel economy level cannot be accomplished by a conventional helicopter given the same payload requirement. A new technology is required, and the tilt rotor can fill the bill. Current estimates place production tilt rotor cost at approximately double that of an equivalent helicopter, with a 10% takeoff gross weight penalty. These values are likely to shrink significantly if sales are successful and development continues, but for the purposes of this analysis, the current projections will be used.

The results of using the listed impacts on Sales is provided in Figures 56.
The 10% increase in fuel economy (the76) results in a 3% increase in Sales relative to the baseline (the75). Meeting a 25% fuel economy improvement regulation (the77) results in a 4.8% improvement in Sales, again a significant improvement. The most stringent fuel economy regulation, the 100% improvement case (the78) gives an unexpected result. As fuel economy increases, the expectation would be for the resulting increase in Payload range to improve Sales, as the 10% and 25% cases have shown. Instead, Sales increases 3%, approximately the same impact as the 10% fuel economy case. The reason for this is the greatly increased cost of the new design concept relative to the baseline helicopter. To prove this, a new case was run where the weight of the new concept was allowed to grow 20% to 12000 lbs, reducing the cost increase from $4,000,000 to $2,000,000. (See Figure 6 for the relationship between cost and weight for rotorcraft). The resulting Sales increase (the80) is 9% higher than the baseline.
5.4 Impacts of Combined Regulations

Since more than one of these regulations can be imposed at the same time, sensitivities for three combinations of regulations were run. These cases were chosen to incorporate the most likely combinations to be seen by the industry by the end of the time period in question. The first combination is shown by the81 in Figure 57. This combines the -9dB acoustic regulations with the emissions level to be imposed on turbofan engines after December 31, 1999. The 10% improved fuel economy regulation is also assumed. The regulation levels chosen are well within the current capabilities of both the government regulators and the industry. The second case (the82) increases the acoustic regulation to the -12 dB case, the emissions regulations to the automotive emissions equivalent and the fuel economy regulation to the 25% improvement level. This case is more of a technology stretch; particularly for the emissions regulations, which would require significant changes to both the vehicle and infrastructure. The final case (the85) continues the -12 dB acoustic level and automotive emissions level, but increases the fuel economy level to 100% improvement. This will require a new platform to meet the fuel economy regulations. The cases are shown in Figure 57 below.

As can be seen from the charts, the first combination (the81) provides a 5% improvement in Sales relative to the baseline (the75). The second case, which incorporates the 25% fuel
economy improvement regulation, shows a 6.5% reduction in Sales relative to the baseline. For this case, the reduction in Sales can be traced primarily to the changes required for the exhaust emissions regulations, which have been increased to the automotive emissions level. This requires severe changes in the aircraft details, resulting in several serious penalties in weight, cost and payload range.

The 85 recovers the loss in sales seen in the 81 and the 82, but requires an entirely new platform (such as the tiltrotor) to accomplish this result. If the platform is not changed, the aircraft modifications required to meet the 100% fuel economy regulations would result in severely prohibitive impacts on the three key parameters (weight, cost and payload range).

6.0 Additional Insights and Recommendations

Table 4 summarizes the sensitivity results described in the previous section. The parameter, the range of variation investigated, the impact on Unit Sales for both the mid-point (4 years) and the end of the time period investigated (8 years) and comments are provided. As can be seen in the table, the sensitivity which provided the greatest increase in Unit Sales is the Completing R&D Workforce, followed by the Retirement Rate, Time Window, the Lobbying Impact on New Regulations and the Technology Impact on Payload Range.

The sensitivities which showed the greatest decrease in Unit Sales were the Lobbying Impact on New Regulations, the Fraction of Revenues to Technology Improvements and the Impact of the Public on Regulations. As noted in the comments, the decrease in Sales resulting from the increase in Fraction of Revenues to Technology Improvement is not an expected result. As noted in Section 4.0 (Figures 42, 43), although increased revenue does produce more technology improvements, the current R&D organization structure does not have the capability to pass these additional improvements on to completion because of a lack of personnel in the identifying, selecting and completing R&D projects areas.
Based on the sensitivity results, a recommended list of changes to improve Unit Sales was compiled. The final list consisted of changes to the Completing R&D Workforce, the Retirement Rate, the Co-location Factor and the Lobbying Impact on New Regulations. There were several other items in Table 4 which had significant positive impact on Unit Sales but were ultimately not included on the recommendation list. For example, both Regulation Research Results and the Impact of the Public on Regulations showed improvement in Sales. But as a practical matter, it would be difficult to influence the regulation research performed by the government in the short term. Similarly, although advertising could influence public opinion, it was decided that the recommendations should concentrate on areas which were in direct control of the client company.

Two other items that provided significant increases in Unit Sales were not part of the recommendations list. These items were the Technology Impact on Payload Range and the Time Window. The Technology Impact on Payload Range was not used since the level of improvement
assumed to achieve the increase in Unit Sales shown in Table 4 was much greater than that actually possible without changing the basic rotorcraft platform. This platform change would be needed for certain combinations of regulation imposition and would be accommodated for those items (See below). For the Time Window, reductions in the time required for individual technology improvements would obviously increase Sales, but would also increase the time to market for future products for both the client company and the competition. Since this was directly opposed to the client company’s current focus, this change was not included in the original recommendations list. It was decided to include the impact of a Time Window change only if the original recommended list was not sufficient to arrest the projected Sales decline. As will be seen in the following section, the original list sufficed.

The Completing R&D Workforce is recommended to be increased 50% from an initial value of 2 people to 3 people. This could be accomplished with no cost by moving experienced personnel slated for retirement. The recommendation for the Retirement Rate itself is a 50% reduction in the current rate. This keeps average productivity high and provides additional personnel for technology improvement processing. This could be easily accomplished by eliminating the recent retirement packages offered by the client company to entice older workers to leave. The co-location factor was increased to 1.0, signifying all personnel working on a particular project will be located in proximity to each other. This improves communication and information maturation time decreases. The final recommendation change is the increase in lobbying activity by 50%. Again, this is relatively easily done, since current lobbying activity is at a very low level. The increasingly global nature of the parent corporation provides additional opportunities to implement this recommendation.

The recommendations were then run and compared to the baseline case for the three examples of possible regulations described in the previous section. The results are presented in Figure 58 below.
The first case, the86, shows the impact of the recommendations for the most likely regulation scenario: -9dB acoustic level reduction, emissions at the January 1, 2000 level for turbofans, and a 10% fuel economy increase. This case shows an increase in Sales of 18% over the baseline at the 4 year point, and a 30% increase at the 8 year point. This essentially returns a flat Sales curve relative to the initial condition. It certainly affords the client company enough time to perform other R&D and consumer surveys to determine what the next course of action should be.

The second case, the87, uses the -12dB acoustic level reduction, emissions for the automobile level regulation, and the 25% fuel economy improvement. This results in an 8% improvement over the baseline at 4 years, and a 16% improvement at 8 years. Although there is a slight falloff from the desired flat Sales curve, the severe degradation of the baseline is no longer the behavior of this system.

The last case, the88 uses the same acoustic and emissions levels as the87, but increases the fuel economy level to a 100% improvement. The resulting Sales curve shows a 14% improvement over the baseline at 4 years, and a 21% improvement at 8 years. This significant improvement over the second case (the87) is primarily the result of the new platform required to reach the required fuel economy levels, as we have seen previously. The Sales curve is essentially flat with a small falloff at the 8 year mark. Again, the time provided for the client company can be used to research the next path the company should take.
7.0 Conclusions
The suggested changes are effective in eliminating the sales decline feared by the client. The recommended changes can be implemented with minor impacts to the company structure in the short term. The additional stable sales trend can provide the time and revenues required to find product advances and/or alternatives which could prevent this situation in the future and bolster the company's competitive position. The model's built-in flexibility could be used to examine behavior changes due to any structure changes indicated by the research results.

With implementation of the recommendations, support of the company's management, and buy-in by the employees, the client company's future can be quite bright.
8.0 REFERENCES


5. FAR Part 36, Noise Standards: Aircraft Type and Airworthiness Certification, through Amendment 36-18; August 18, 1990, issued by the Office of Environment and Energy, Federal Aviation Administration, Office AEE-110.

6. FAR Part 91, Subpart I, Operating Noise Limits, issued by the Office of Environment and Energy, Federal Aviation Administration, Office AEE-300.

7. FAR Part 150, Airport Noise Compatibility Planning; Revised 10/25/89, issued by the Office of Environment and Energy, Federal Aviation Administration, Office AEE-300.


12. AC 150/5020-1, Noise Control and Compatibility Planning for Airports; August 1983, issued by the Office of Environment and Energy, Federal Aviation Administration, Office AEE-300.


15. FAA Notice N7210.360, Noise Screening Procedures for Certain Air Traffic Actions Above 3,000 Feet AGL, issued by the Office of Environment and Energy, Federal Aviation Administration, Office AEE-120.

REFERENCES, cont’d


9.0 List of Variables

Actual Cost = ("Reg. Impact on Cost" + Technology Impact on Cost) + Initial Cost
Units: dollars

Units: lb*nm

Actual Weight = ("Reg. Impact on Weight" + Technology Impact on Weight) + Initial Weight
Units: lb

Adding New Potential Regs = Impact of Public on New Regs * Regulation Research Results * Lobbying Impact on New Regs
Units: regulation/Month

Adjusted Competitive Advantage = Competitive Advantage * PressureToAdjust Competitive Advantage
Units: dmnI

Adjusted Technical Risk = Technical Risk * PressureToAdjust Technical Risk
Units: probability of failure

Approval Completion = Regs in Congress * Impact of Public on Approval * Lobbying Impact on Approval
Units: regulation/Month

Attractiveness of Competitor's Product = 0.9
Units: dmnI

Average Price = 4e+006
Units: dollars/helicopters

Average Productivity = production/Workforce
Units: projects/people/Month

ChangelnCompetitive Advantage = (Adjusted Competitive Advantage - Competitive Advantage) / Time to change competitive advantage
Units: dmnI/Month

ChangelnTechnical Risk = (Target Tech Risk - Technical Risk) / competitive time window
Units: probability of failure/Month

"Co-location Extent" = 0.5
Units: dmnI

Competitive Advantage = INTEG (ChangelnCompetitive Advantage, InitialCompetitive Advantage)
Units: dmnI

Competitive Advantage Info
f([[0,0,0,0,0.00877193], [0.217523, 0.219298, 0.465257, 0.460526, 0.655589, 0.649123, 0.806647, 0.811404, 0.993958, 1]])
Units: dmnI
competitive time window=10
Units: Month

"Completing R&D"=AverageProductivity*Workforce
Units: projects/Month

Correct Information= INTEG (Info Quality Improving-Obsolete Information,50)
Units: data

Cost Factor=20000
Units: dollars/regulation

Cost Risk Adjustment Factor=Technical Risk*1.2
Units: probability of failure

Creation power iding=0.001
Units: technologies/projects

"creation power R & D"=0.05
Units: technologies/projects

creation power selecting=0.002
Units: technologies/projects

Effect of Market Share on Tech Risk
f([(0,0)-(1,1)],(0.00302115,0.995614),(0.18429,0.811404),(0.380665,0.622807),
(0.628399,0.381579),(0.785498,0.223684),(0.996979,0.00438596))
Units: dmnl

"Effect Of PL/R On Attractiveness"="EffectOfPayload/RangeOnAttractiveness f"(Actual PayloadRange/300000)
Units: dmnl

EffectOfCostOnAttractiveness=EffectOfCostOnAttractiveness f(Actual Cost/4e+006)
Units: dmnl

EffectOfCostOnAttractiveness
f([(2,-2)-(2,2)],(-1.98792,1.98246),(-0.984894,1.5614),(-0.344411,0.912281),
(0.0060423,-0.0175439),(0.52568,-0.982456),(1.33535,-1.57895),(2,-1.94737))
Units: dmnl

"EffectOfPayload/RangeOnAttractiveness
f"([(3,2)^(-3,2)],(-1.98792,1.98246),(-1.44109,-1.45614),(-0.480363,-0.859649),
(-0.2271903,0.0175439),(0.661631,0.894737),(1.76737,1.63158),(2.96375,2))
Units: dmnl

EffectOfWeightOnAttractiveness=EffectOfWeightOnAttractiveness f(Actual Weight/10000)
Units: dmnl

EffectOfWeightOnAttractiveness
f([(2,-2)-(2,2)],(-1.98792,1.98246),(-1.03323,1.31579),(-0.404834,0.701754),
(0.0181269,-0.0350877),(0.549849,-0.964912),(1.3716,-1.57895),(1.97583,-1.96491))
Units: dmnl
Experienced = INTEG(Maturing - GainingWisdom, Maturing *TimeForExperiencedToGainWisdom)
Units: people

ExperiencedProductivity=0.0825
Units: projects/people/Month

FINAL TIME = 100
Units: Month

Fraction of Revenues to Technology Improvement=0.05
Units: dmnl

GainingWisdom = Experienced / TimeForExperiencedToGainWisdom
Units: people/Month

General Information Collection=4
Units: data/Month

GrayHairProductivity=0.125
Units: projects/people/Month

GrayHairs = INTEG(GainingWisdom - Retiring, GainingWisdom*TimeForGrayHairToRetire )
Units: people

Hiring=0.33
Units: people/Month

ID'd needs obsol=Identified needs/competitive time window
Units: projects/Month

Identified needs= INTEG (IDing needs-Selecting projects - ID'd needs obsol,
(IDing needs-Selecting projects)*competitive time window)
Units: projects

IDing needs=IDPeople*IDPdy
Units: projects/Month

IDing Regs=((Impact of Public on IDing*Remaining Potential Regulations)*Money Available for Technology Improvements/(Technology Improvements Available*Technology Improvement Factor)) * Lobbying Impact on IDing
Units: regulation/Month

IDPdy=4
Units: projects/(Month*people)

IDPeople=3
Units: people

Impact of Public on Approval=1.005
Units: dmnl

Impact of Public on IDing=1.05
Units: dmnl
Impact of Public on New Regs=1.2
Units: dmnl

Impact of Public on Repeal=0.01
Units: dmnl

Impact of Public on Selecting=1.02
Units: dmnl

Implemented Regulations= INTEG (Approval Completion-Regulation Repeal,10)
Units: regulation

Incorrect Information= INTEG (+Obtaining Information-Info Quality Improving,100)
Units: data

Increasing Technology Base=New Technologyfrom IDing+New Technology from selecting:+"New Technology from R&D"
Units: technologies/Month

Industry Unit Sales=40
Units: helicopters

Info Quality Improving=Incorrect Information/Time for Info Quality to Improve
Units: data/Month

Information Generation Factor=0.1825
Units: data/people/Month

Initial Cost=4e+006
Units: dollars

Initial Payloadrange=300000
Units: lb*nm

Initial Technical Risk=0.8
Units: probability of failure

INITIAL TIME = 0
Units: Month

Initial Weight=10000
Units: lb

Initial Competitive Advantage=0.5
Units: dmnl

Lobbying Impact on Approval=0.95
Units: dmnl

Lobbying Impact on IDing=0.25
Units: dmnl

Lobbying Impact on New Regs=0.25
Units: dmnl
Lobbying Impact on Selecting = 0.5
Units: dmnl

Lobbying Impact on Repeal = 0.95
Units: dmnl

Market Share for Competitor’s Product = 1 - Market Share for Product
Units: dmnl

Market Share for Product = Product Attractiveness / Total Attractiveness
Units: dmnl

Maturing = Rookies / Time For Rookie To Mature
Units: people/Month

Maximum Attractiveness = 1
Units: dmnl

Minimum Technical Risk = 0.2
Units: probability of failure

Money Available for Technology Improvements = SMOOTH(Fraction of Revenues to Technology Improvement * Our Revenues, Time window)
Units: dollars

"New Technology from R&D" = "Completing R&D" * "creation power R & D"
Units: technologies/Month

New Technology from selecting = Selecting projects * "creation power selecting"
Units: technologies/Month

New Technology from IDing = IDing needs * "creation power IDing"
Units: technologies/Month

Obsolescence = Technology Improvements Available / competitive time window
Units: projects/Month

Obsolete Information = Correct Information / Time to Obsolescent Info
Units: data/Month

Obsoleting Technology Base = Technology Base / competitive time window
Units: technologies/Month

Obtaining Information = General Information Collection + ("Co-location Extent" * Workforce * Information Generation Factor)
Units: data/Month

Our Revenues = Average Price * Our Unit Sales
Units: dollars

Our Unit Sales = Industry Unit Sales * Market Share for Product
Units: helicopters

payloadrange factor = -3000
Units: lb * nm / regulation
Payloadrange Risk Adjustment Factor = Technical Risk * 1.5
Units: probability of failure

PressureToAdjust Competitive Advantage = Competitive Advantage Info (Correct Information / 125)
Units: dmnl

PressureToAdjust Technical Risk = Effect of Market Share on Tech Risk (Market Share for Product)
Units: dmnl

Units: dmnl

Production = Rookies * Rookie Productivity + Experienced * Experienced Productivity +
GrayHairs * Gray Hair Productivity
Units: projects/Month

Project Cost Factor = 100,000
Units: dollars/projects/Months

Projects in Technology Base = 25
Units: projects/technologies

"R&D projects obsol" = "Technology Improvement Projects in R&D" / competitive time window
Units: projects/Month

Refilling the well = (Increasing Technology Base * Projects in Technology Base) + (Money Available for Technology Improvements / Project Cost Factor)
Units: projects/Month

"Reg. Impact on Cost" = Implemented Regulations * Cost Factor
Units: dollars

"Reg. Impact on PayloadRange" = Implemented Regulations * Payloadrange factor
Units: lb*nm

"Reg. Impact on Weight" = Implemented Regulations * Weight Factor
Units: lb

Regs ID'd for Implementation = INTEG (IDing Regs-Selecting Regs, 20)
Units: regulation

Regs in Congress = INTEG (Selecting Regs-Approval Completion, 20)
Units: regulation

Regulation Repeal = Implemented Regulations * Impact of Public on Repeal * Lobbying Impact on Repeal
Units: regulation/Month

Regulation Research Results = 10
Units: regulation/Month

Remaining Potential Regulations = INTEG (Adding New Potential Regs-IDing Regs, 10)
Units: regulation
"Remaining tech. improv. potential \"The Well\"= INTEG (Refilling the well-The well obsol-IDing needs,100)
Units: projects

Retiring = GrayHairs / TimeForGrayHairToRetire
Units: people/Month

RookieProductivity = 0.05
Units: projects/people/Month

Rookies = INTEG(Hiring - Maturing, Hiring*TimeForRookieToMature )
Units: people

SAVEPER = TIME STEP
Units: Month

Selecting projects = Selectpeople*SelectPDY
Units: projects/Month

Selecting Regs = (Impact of Public on Selecting+Regs ID’d for Implementation)*Lobbying Impact on Selecting
Units: regulation/Month

SelectPDY = 2
Units: projects/(people*Month)

Selectpeople = 2
Units: people

Target Tech Risk = MAX(Adjusted Technical Risk, Minimum Technical Risk)
Units: probability of failure

Tech Cost Improvement Factor = -25000
Units: dollars/projects

Tech PLR Improvement Factor = 3000
Units: lb*nm/projects

Tech Weight Improvement Factor = -50
Units: lb/projects

Technical Risk = INTEG(ChangeInTechnical Risk, Initial Technical Risk)
Units: probability of failure

Technology Base = INTEG (Increasing Technology Base-Obsoleting Technology Base,6)
Units: technologies

Technology Impact on Cost = Tech Cost Improvement Factor*Technology Improvements Available*(1-Cost Risk Adjustment Factor)
Units: dollars

Technology Impact on Payloadrange = Tech PLR Improvement Factor*Technology Improvements Available*(1-Payloadrange Risk Adjustment Factor)
Units: lb*nm
Technology Impact on Weight = Tech Weight Improvement Factor * Technology Improvements Available * (1 - Weight Risk Adjustment Factor)
Units: lb

Technology Improvement Factor = 1e+007
Units: dollar/(projects/Month)

'Technology Improvement Projects in R&D' = INTEG (+ Selecting projects - 'Completing R&D' - 'R&D projects obsol', (Selecting projects - 'Completing R&D') * competitive time window)
Units: projects

Technology Improvements Available = INTEG ('Completing R&D' - Obsolescence, 'Completing R&D' * competitive time window)
Units: projects

The well obsol = 'Remaining tech. improv. potential \"The Well\"' / competitive time window
Units: projects/Month

Time for Info Quality to Improve = 6
Units: Month

TIME STEP = 1
Units: Month

Time to change competitive advantage = 3
Units: Month

Time to Obsolescent Info = 18
Units: Month

Time window = 20
Units: Month

TimeForExperiencedToGainWisdom = 48
Units: Month

TimeForGrayHairToRetire = 60
Units: Month

TimeForRookieToMature = 24
Units: Month

Total Attractiveness = Attractiveness of Competitor's Product + Product Attractiveness
Units: dmnl

Weight Factor = 25
Units: lb/regulation

Weight Risk Adjustment Factor = Technical Risk * 0.8
Units: probability of failure

Workforce = Rookies + Experienced + GrayHairs
Units: people