A SYSTEM DYNAMICS MODEL OF THE DEVELOPMENT CYCLE FOR FUTURE MOBILITY VEHICLES

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Abstract

In the development of future air vehicles, a large number of inter-disciplinary areas come into play. An overall transportation framework is introduced and key agents to a mobility value network are identified. A simulation of the overall system is needed, but the present paper focuses on the aspect of product development for a future vehicle manufacturer. A System Dynamics model is developed to investigate the importance of product development lead time and design failure rate. The effect of uncertainty is explored through Monte Carlo simulation. The case results show the manufacturer's net profit to be more sensitive to design and certification lead time, as compared to a lower development failure rate. In this scenario, a policy that rewards the early completion of work more than higher design success rate would be effective for the manufacturer. This study represents the initial step towards modeling the dynamics within a system-of-systems mobility environment.

Introduction

The context of the presented research lies in the evaluation of future air vehicles. These vehicles are expected to have significantly increased performance and affordability characteristics, which are impossible to achieve with current technology capabilities. The goal of these vehicles is to provide enhanced mobility to a large number of the population and revolutionize current transportation paradigms. Enhanced mobility refers to the capability to save travel time, take more trips or even travel to further destinations. The potential impact of disruptive technologies has been well documented by Christensen [1] and its implications have been realized in many technology intensive industries. "Disruptive" technologies refer to new innovations that have the potential to displace mainstream market products in the future, although currently lacking comparatively in cost or functionality. The Inter-Urban Vehicles (IUV) concept is one such example, which is an envisioned personal air mobility alternative that could revolutionize the transportation industry through affordable on-demand travel. The new paradigm for IUV design is not just to provide for an efficient vehicle but to provide enhanced mobility. Integration with current transportation modes has to be considered and issues such as overcapacity and delay, as has plagued the transportation industry, are also essential in the process of enhancing mobility.

Aerospace designers have long relied on requirements set forth by existing customers. But for disruptive technologies with no established markets or existing infrastructure such guidance is no longer available. Hence before any kind of design activity takes place, designers must first determine the minimum requirements needed for the concept to successfully pass through every facet of the design, development, testing, manufacturing and marketing process. For a de-

sign effort related to improving future transportation, these questions can be answered through a thorough understanding of the mobility value network as shown in Figure 1 [1, 2].
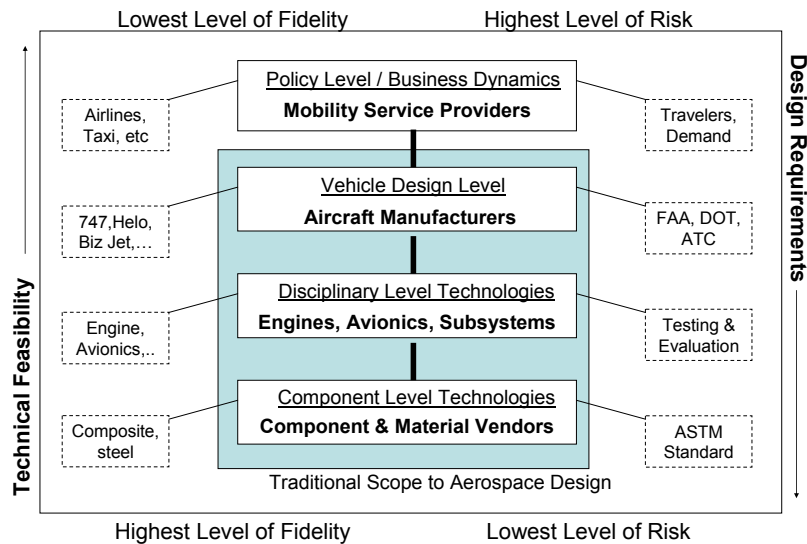

Figure 1 – Mobility Value Network Diagram

Design requirements are propagated in a top-down fashion from the policy level to the component level technologies while the technical feasibility is determined from the bottom up. A different value criterion exists at each stage as each organizational entity answers to different customers. For example, airlines would cater to travelers and aircraft manufacturers would be responsible towards airlines and the FAA. The policy level dynamics, which is typically neglected in the aerospace design phase, usually contributes the highest level of risk to the program.

The policy level dynamics of the entire subset of mobility stakeholders is shown through Figure 2. Unlike a software development firm, for example, where the major interaction only occurs between the development team and consumers [3], the transportation industry is interlinked by a complicated web of commercial firms, governing agencies and infrastructure providers. Traditionally, design focus has been placed on the interaction between research, manufacturing and safety regulations. For future air vehicles where no information regarding the other stakeholder is available, a "big-picture" perspective to design becomes necessary. This is referred to as a "System-of-Systems" view, where all the mobility stakeholders are taken into consideration in the design process. While there has been no shortage of innovative air vehicle concepts in the past, implementation of new ideas in the transportation industry is becoming increasingly difficult with more interest groups involved in the decision making. Future innovation in air transportation would not be solely in radical vehicle designs but in managing the interfaces between these inter-disciplinary fabrics.
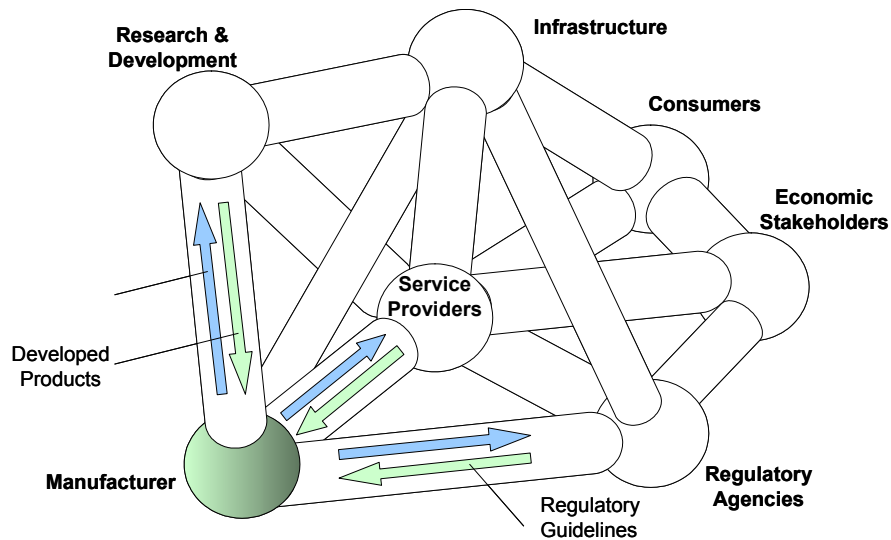
Figure 2 – Mobility Stakeholder Network

The mobility stakeholder network can also be viewed as a simple causal relationship diagram for the air transportation industry. Each link between the stakeholders represents a relationship, or a two-way flow of 'stock'. For the research agencies-to-manufacturer link, this stock may represent funding for research programs and developed product designs for manufacturers. Many of the design efforts undertaken by research agencies do not relate directly to the consumers whose lives may be impacted by the advances in technology. Transportation service-providers on the other hand, are more significantly impacted by consumer trends but do not have direct control over technology development programs. For a new air vehicle concept to be successful, efficiencies in each stakeholder relationship must be maximized and the information available at later stages has to be predicted during the early design phase to ensure a higher overall success rate as well as a lower redesign cost.

A more detailed representation of the relationships between mobility stakeholders is shown in Figure 3. Stakeholders are listed in the rows and columns, thus the diagonal contains the modules that represent the function of each stakeholders' strategic enterprise. For example, the Aircraft Design & Research module simulates the decision making of research agencies, and the Production & Financial Dynamics module represents the decision making behavior of aircraft manufacturers. Complexity in the relationships between the stakeholders exists on many levels. The primary purpose of the diagram in Figure 3 is to illustrate all the possible relationships to aid our mental models. In this sense, it is a precursor to a causal loop diagram. However, added complexity beyond a certain level only serves as a detriment to model validity as compared to additional insight. Thus, based on the characterization of the strength of the relationship, only the strong feedback links may be quantitatively modeled. The variables that feed into each module are categorized into strong, medium and weak levels of relationship, and the strong relationship variables form the majority of the links shown earlier in Figure 2. The direction of the arrows also indicates the feed-forward or feedback nature of the flow of resources. For example, 'Finalized designs' are fed forward from the Aircraft Design & Research module to the Production & Financial module. 'Research Funding' and 'Vehicle Requirements' are in turn fed back to the first module. This block serves as the realm of exploration using System Dynamics and described in this paper.

3 - Strong Relationship 2 - Medium Relationship 1 - Weak Relationship

	Research Agencies	Aircraft Manufacturers	Regulatory Agencies	Infrastructure Providers	Transportation Service Providers	Economic Development Stakeholders	Consumers
Research Agencies	**Aicraft Design & Research module**	↓3 Finalized Designs, Feasibility studies	↓1 Technology Research	↓1 ATC Technology Research	↓1 Technology Forecasting	↓1 Publicly available research reports	↓1 Publicly available research reports
Aircraft Manufacturers	↑3 Research Funding, Vehicle requirements	**Production & Financial Dynamics**	↓2 Vehicle data, Compliance needs	↓2 Vehicle navigation capability	↓3 Aircraft, Maintenance Support	↓3 Job creation, tax contributions	↓1 Vehicle Attractiveness
Regulatory Agencies	↑2 Design guidelines for safety	↑3 Aircraft Certification	**Regulatory Standards module**	↓3 Infrastructure Certification	↓3 Operating Guidelines, Security check	↓1 Public confidence in transportation safety	↓2 Public confidence in transportation safety
Infrastructure Providers	↑2 Design guidelines for infrastructure compatibility	↑1 Infrastructure guidelines	↑3 Infrastructure data, ATC compliance needs	**ATC Network & Infrastructure module**	↓3 Airports, Runways, ATC	↓3 Economic growth, job creation	↓3 Convenience of Travel
Transportation Service Providers	↑3 Design guidelines for vehicle performance	↑3 Vehicle Purchase Demand	↑3 Operation data, Operation compliance needs	↑3 Operation data, Capacity needs	**Service Network, Financial Dynamics**	↓3 Economic growth, job creation	↓3 Cost Effectiveness of Travel, Speed
Economic Development Stakeholders	↑1 Research Data, Government Funding	↑1 Labor supply, economic benefits	↑2 Environmental compliance needs	↑2 Labor supply, city transportation requirements	↑3 Labor supply, economic benefits	**Macroscopic Economic Development**	↓3 Public Transportation modes
Consumers	↑2 Design guidelines for vehicle configuration	↑2 Market Investment	↑1 Public opinion on safety	↑1 Traveler Preferences	↑3 Traveler Preferences	↑3 Taxes, Human Resources	**Consumer Trends**

Figure 3 – Relationship Matrix between Mobility Stakeholders

The research challenge in the field of mobility dynamics is the creation of a modeling framework where each of the stakeholder relationships is quantified through simulation methods such as System Dynamics. A System Dynamics formulation for part of the mobility framework appears appropriate and useful for many reasons. It facilitates the simulation of the feedback links within a complex system as well as the effect of policy over a prescribed time period. System Dynamics is also well suited to the level of modeling detail necessary for the aforementioned needs. At a system policy level, the emphasis does not lie in simulating and validating a detailed model but rather on assessing a problem through policy simulation exercises.

The simulation work discussed in this paper focuses on the relationship that an aircraft manufacturer has with the product development process (highlighted portions in Figures 2 & 3). Results discussed pertain to sensitivities of management policies that the manufacturer may adopt within the company or with other entities. An example would be shortening the product development lead time by hiring more research staff or by reducing the redesign workload through quality control. The primary value of the aircraft development cycle model is in the creation of a module which can now be linked to other stakeholder modules in the future.

Problem Definition – IUV Manufacturer's Policy Analysis

A vehicle manufacturer plans to develop and launch a new generation of IUVs on the market. Demand for mobility solutions is practically limitless since it addresses a fundamental societal need. However, growth of the industry is limited by instabilities of the economy as well as instabilities in the development cycle. One of primary goals of company management is to expand its market share of mobility products while maintaining a positive balance sheet. Many IUV concepts developed in the research laboratories are often abandoned before reaching the end of the development cycle. This is due to the large uncertainties that exist due to insufficient information at the developmental stage. These uncertainties are propagated from other stakeholders and causes scheduling and quality problems for the research team.

The development of a new IUV takes an average of 4 years from initial concept defini-tion to product release. The introduction of a new IUV into the market reduces the average travel time and hence increases the customer base for the IUV. This is due to travelers now being able to travel to further destinations, take more number of trips, or make trips not possible before. The cost of the new IUV is comparatively higher than other transportation modes but decreases over time due to larger production quantities. IUV concepts typically have a market life of 5 years, after which the product models are retired and taken off the market. The development of each IUV prototype represents a significant capital investment for the company and a huge concern for management is the ability of the company to forecast future demand for IUVs and manage risk in the development process. A design prototype that is not certifiable or misses the market window for product launch provides no positive return for initial research investment. Thus the specific problem to be solved is determining the significance of the development delay time and design failure rate for the manufacturer.

Implementation of a System Dynamics Approach

The simulation model traces the flow of IUV designs, from when the idea was first con-ceived to when the product is finally retired from the market. An initial investment is specified and an increase in cash flow occurs only after the first batch of products is introduced into the market. The flow of revenues to the design inception phase acts as a reinforcing feedback and the challenge for the manufacturer is in overcoming the design, certification and production lead times. The primary model variables of interest are listed as in Table 1, including a "Connected to" column that relates to Figure 3.

Table 1 – Model Variable List

Variable Name	Description	Connected to
Fraction Failed	Fraction of Projects that fail design feasibility test or FAA certification test	Research groups, Regulatory agencies
Fraction Failed Redesign	Fraction of Projects that fail design feasibility test even after redesign or after delaying FAA certification test	Research groups, Regulatory agencies
Revenue per product	Revenue earned by Manufacturer per product, after taxes, production and miscellaneous expenses ($ millions)	Service Providers, Consumers
Initial Capital	Initial capital investment for product launch	Economic stakeholders, Consumers
Cost per Project Development	Cost to design, test and certify a vehicle ($ millions)	Research groups, Regulatory agencies
Fraction Payout	Fraction of product revenue used to pay debt and dividends	Manufacturer Policy
Interest Rate	Interest rate	Economic stakeholders
Cost Inflation Rate	Inflation rate	Economic stakeholders
Product Market Life	Average number of years that a product stays in the market before being retired	Manufacturer Policy, Service Providers
Design & Certification Lead Time	Average number of years need to design, test and certify a vehicle concept	Research groups, Regulatory agencies
Redesign and Certification Lead Time	Average number of years needed to redesign or added certification time	Research groups, Regulatory agencies
Production & Marketing Lead Time	Average number of years needed to prepare for maufacturing and product introduction	Manufacturer policy, Economic stakeholders

The causal loop diagram of the IUV Manufacturer's development cycle is shown in Fig-ure 4. Much of the information is relevant to and hence referenced from Coyle's example of a pharmaceutical company [4]. The solid lines refer to a physical flow of material (stock and flow) while the dashed lines only represent a flow of information (influencing variables). The

primary feedback presented in this example is the flow of Disposable Revenue from current products in market back to product research and the key aspect is the two delay modules of product research and product introduction, as well as the delay module of product retirement.

Figure 4 – Causal Loop Diagram [4]

The stock and flow model developed using STELLA$^©$, is shown in Figure 5. The stock referenced as "*Product Ideas*" represent a pool of research development projects in the early development stage. The rate at which this increases is determined by the average costs associated with each developmental project and the resources pooled from the company cash flow. "*Completed Designs*" represent projects at the end of the development stage that has passed the feasibility criterion. "*Rejected Designs*" represent product ideas that have failed the feasibility criterion. These failed concepts go through a redesign process, at the end of which the products are tested again. The average design and certification lead time is 3 years and the projects that fail the first feasibility test undergo an extra year of redesign and testing to achieve the required standard. A lead time of a year for production scheduling and marketing is then required before the new products can be first introduced to the market. The number of products in the market determines the company's revenues for the year, based on the average revenue achieved per product. Due to decreasing revenues with product age, products 5 years and older are retired from the market to make way for newer configurations. The "*Cash Flow*" stock is initially representative of the capital investment and subsequently represents the revenues from product introductions. Before revenues are earned all expenditures involved go towards bring the first batch of vehicle concepts to market, and following that, a percentage of the revenues go toward repaying debt and payment of dividends to investors.

The model is simplified by aggregating the delay times of the multiple design and testing phases into one delay process (refer to *DP logic* in Figures 5 & 6). This level of abstraction may be insufficient to address a different problem of identifying the congested segment of the devel-

opment cycle that increases delay time. However, for the prescribed problem of measuring the significance of the development delay time and design failure rate, the level of detail is adequate.
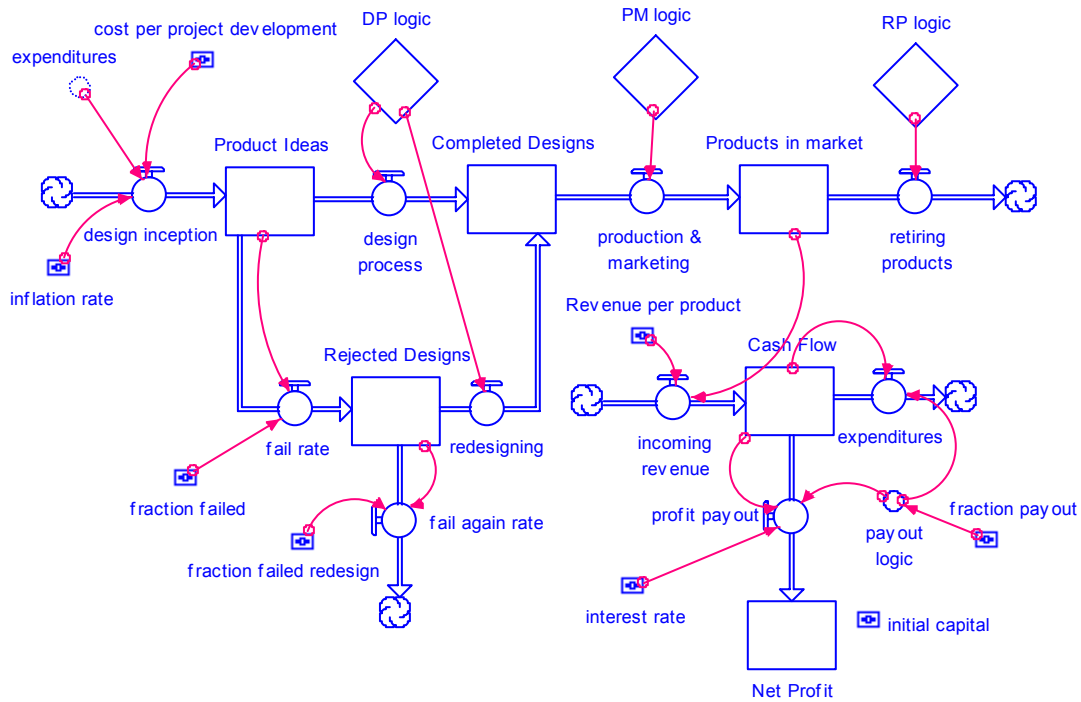

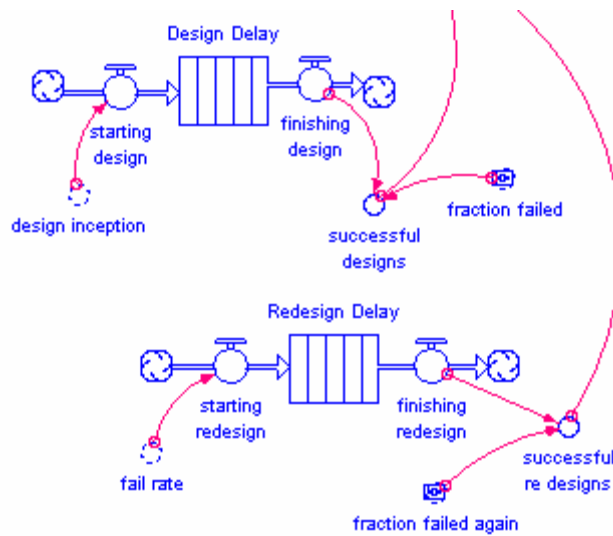Figure 5 – Stock and Flow model of the product development cycle

Figure 6 - Stock and Flow model of the Design Process delay (DP logic)

Model Validation and Testing

In System Dynamics literature, several guidelines are offered for model validation and testing. These include validating the influence diagram with the statement of the problem, dimensional validity throughout the model, and simulation results that stay within reasonable boundaries. These methods were employed to test the validity of the manufacturer's model described earlier, and the baseline results display the reality of the model to a reasonable extent.

Coyle suggests that a more suitable definition to model validity is one that is "well suited to its purpose and soundly constructed" [4]. The primary purpose of the presented model is to examine the importance of design & certification lead time and design failure rate for an IUV manufacturer, and to establish links to other mobility stakeholder modules in a system of system construct. In terms of meeting the problem objective with sufficient simplicity, the model is believed to be adequate. The baseline simulation analysis is performed with the assumptions as shown in Table 2.

Table 2 – Variable settings for baseline simulation run

Variable Name	Value	Units
Fraction Failed	0.5	
Fraction Failed Redesign	0.5	
Revenue per product	65	$ million
Initial Capital	80	$ million
Cost per Project Development	10	$ million
Fraction Payout	0.5	
Interest Rate	8	%
Cost Inflation Rate	8	%
Product Market Life	5	years
Design & Certification Lead Time	3	years
Redesign and Certification Lead Time	4	years
Production & Marketing Lead Time	1	years

The simulation results for the baseline settings are shown in Figure 7. "Net Profit" refers to the cumulative total net present value of the investment thus far, and it can be seen that breakeven occurs at year 8, the 4th year after first product launch. The revenues generated from the products in market from years 4 onwards contribute to the cash flow of the company sufficiently to provide funding for the next generation of products. The baseline scenario results accurately represent a typical situation for aircraft manufacturers, with long development lead times and the financial viability of the company being highly dependent on the success of its initial product offerings.
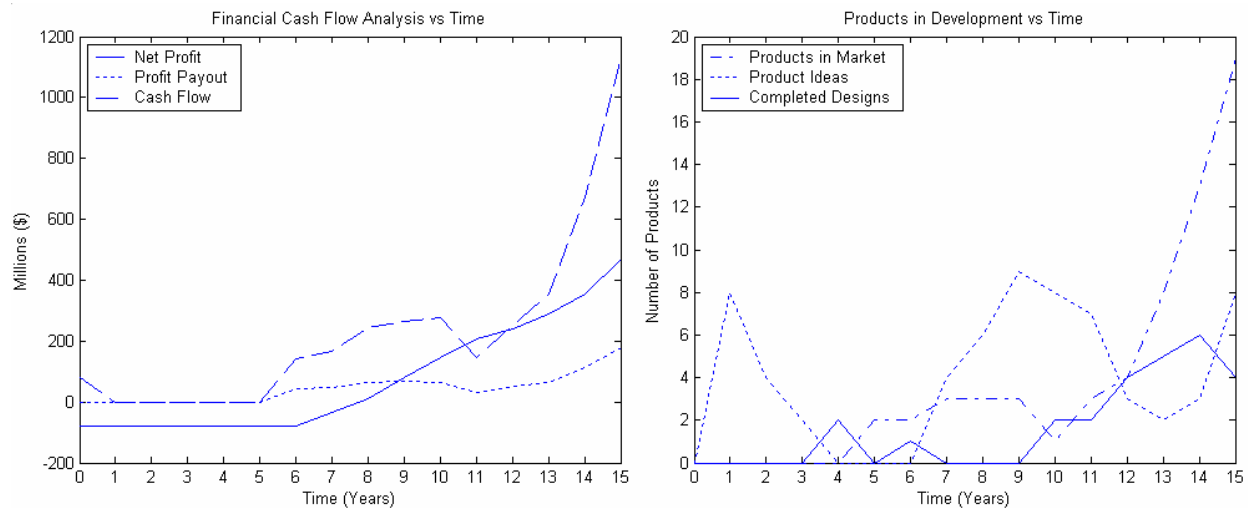

Figure 7 – Results from Baseline analysis

The simulation results for a scenario with higher development costs and lower revenues generated per product is shown in Figure 8. With 30 million dollars of revenue generated per year per product, 100 million dollars of startup capital and a development cost per project of 20 million dollars, the manufacturing company is not viable beyond its first range of product entries. This scenario is not highly realistic since it does not give consideration to learning curve effects or future anticipatory reaction by management to increase revenue or reduce cost. However, under extreme conditions, the results do correlate with expected outcome and reinforces confidence in the validity of the model before an additional layer of detail is built into the model.
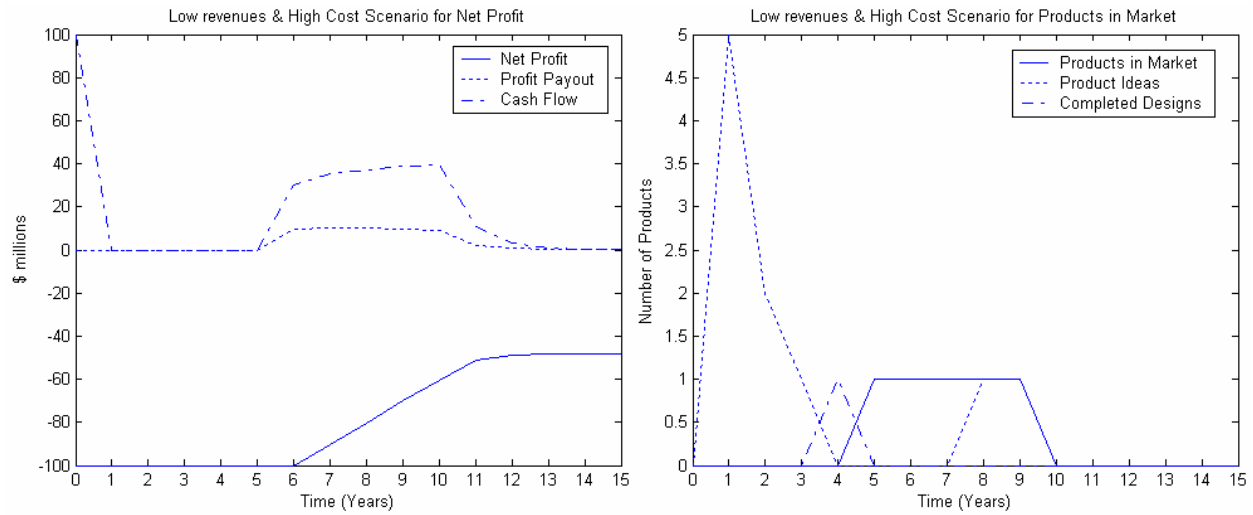
Figure 8 – Lower revenues with higher development costs per product

Simulation Results and Discussion

The problem under study is the link between research and manufacturing and determination of preferred policy. In the link between research and manufacturing, the key barriers to success are the design failure rates as well as the design & certification delay time. Design projects that do not progress to the expected level of maturity do not represent any value to the manufacturer despite significant initial investments [5]. Hence the importance of the design failure rate and the design and certification delay time cannot be over emphasized. The primary results observed for the simulation is the manufacturer's sensitivity to product design and certification lead time as well as design and certification failure rate. It is a widely accepted fact that these two factors are critical to a manufacturer's financial profit, but to an unknown extent. The two factors are also not entirely independent of each other. Rushed design work would likely be lacking in terms of quality compared to one that has gone through a normal cycle time, and vice versa. Should management policy direct effort to better quality control or shorter development lead time? Several scenario results are shown in Figure 9.
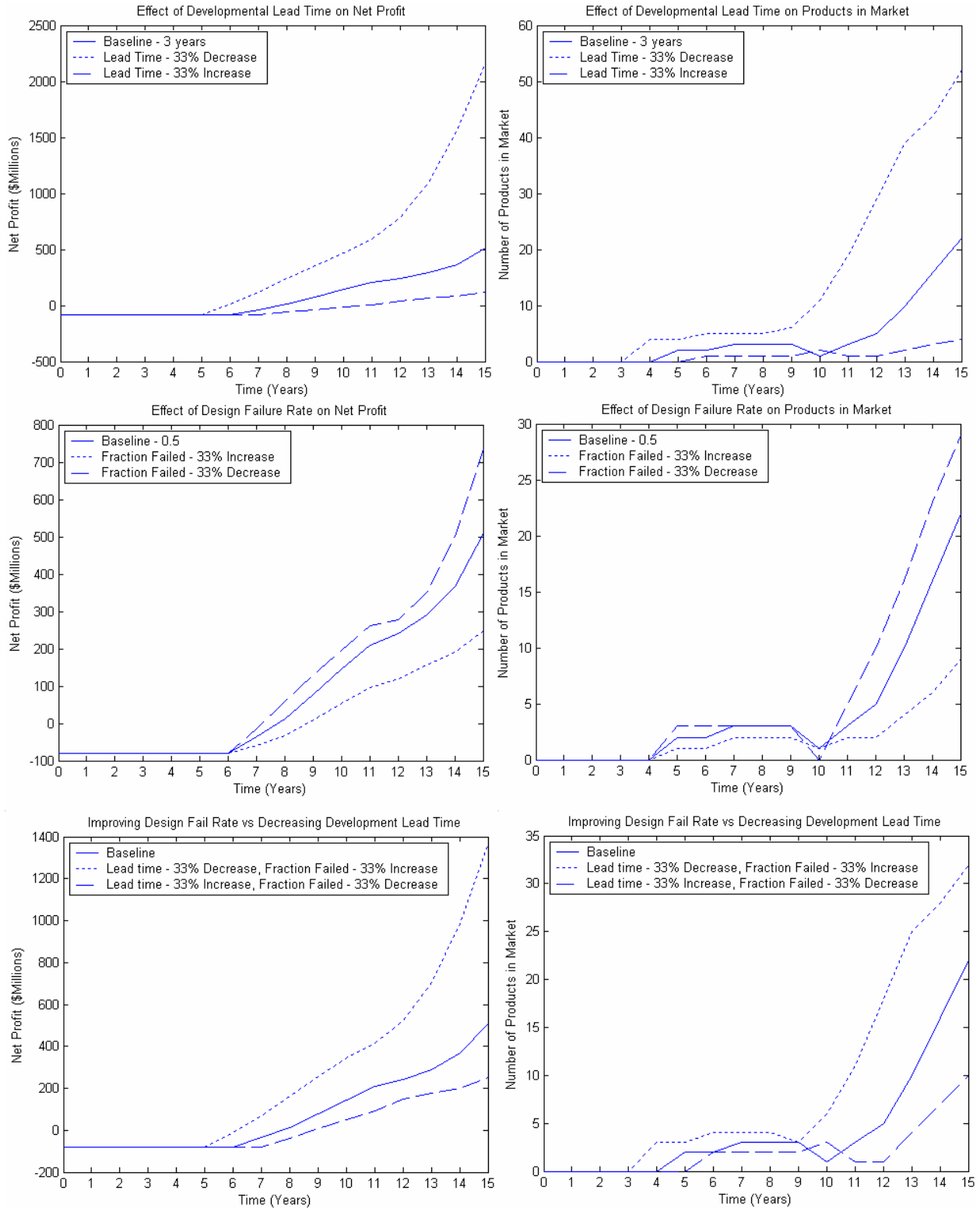
Figure 9 – Effect of Development Lead Time and Fail Rate

The sensitivity of the total Net Profit to a shorter design & certification lead time of the manufacturer appears to be much more significant compared to a lower development failure rate.

A significant advantage of a shorter development time is also being able to return a profit much earlier. The positive gain from better design quality is also important but significant gains are only realizable further in the future. One applicable policy the manufacturer can learn from this exercise is the distribution of design work and research funding to research agencies. With a priority on shortening development time, individual technology portfolios may be integrated and its development supervised as a whole. Aerospace technology development typically takes place at multiple locations, each with different areas of expertise. NASA conducts research also in a distributed network structure, with independent contractors filling in many of the gaps. While the quality of the individual work may be higher, the time it takes to integrate the pieces significantly increases development time. For a manufacturing company depending on profits and not government subsidies to survive in the marketplace, an efficiently integrated development process may be the most critical aspect.

Reinertsen describes that research developmental projects are almost never completed ahead of schedule [5]. They either finish on time or are delayed by an uncertain amount of time. There is not significant incentive for early completion of work, and emphasis in the research labs is always more driven towards successful demonstration of the technology. Based on the presented scenario results, it appears that a research policy that rewards the early completion of work more than higher design success rate may be more effective for the manufacturer in the long term.

Another important question constantly on the mind of any policy maker is the issue of uncertainty. Even with the best of planning, an unexpected downturn in the economy may force the company towards financial instabilities. To simulate the effects of uncertainty, a Monte Carlo Simulation was performed with a uniform distribution placed on the variables shown in Table 3. The uncertainty ranges were selected with the baseline values as mid-points except for the "*Cost per Project Development*" (research spending is never less than the initial budgeted amount but often goes over the budget). Uncertain certification requirements are reflected on the "*Fraction Failed*" variable. A Monte Carlo Simulation is simply a random number generator that selects a variable setting from its distribution and performs the analysis a large number of times repeatedly. With a sufficient number of analysis runs, an accurate assessment of the probability of an event occurring can be predicted. A uniform distribution was used to reflect the lack of knowledge on the uncertainty of the variables used. With a more specific context applied, more refined distributions can be applied to add confidence to the simulation.

Table 3 – Uncertainty range of variables

Variable Name	Range	Units
Fraction Failed	0.4 - 0.8	
Fraction Failed Redesign	0.4 - 0.8	
Revenue per product	30 - 80	$ million
Cost per Project Development	10 - 20	$ million
Interest Rate	3 - 12	%
Cost Inflation Rate	3 - 12	%

With current software modeling capabilities in STELLA$^{©}$, a significantly large number of runs could not be performed easily. Hence, 500 simulation runs were performed and the results for Net Profit are displayed in Figure 10. The histogram displays the extent of risk present, assuming the range and shape of the uncertainties expected from the variables. Assuming a success criterion of a Net Profit of greater than 100 million dollars after year 15, the probability of suc-

cess is measured to be approximately 35%. Furthermore, nearly 24% of the simulation runs return a negative net profit after year 15. The spread of the Net Profit distribution in Figure 10 is observed to be much less than the spread in Net Profit due to changed lead time, from Figure 9. Similar results exhibited from a more through simulation exercise, would support a clear policy recommendation to reduce lead time, despite uncertainties present due to missing information.

An important aspect for future work is the incorporation of more accurate implementation of Monte Carlo Simulation, perhaps through the use of MATLAB$^{©}$ or Crystal Ball$^{©}$. The measurement of risk in the mobility stakeholder is important also in another aspect. Typically in a robust design environment, designers use optimized control variable settings to minimize overall sensitivity to noise variables. Control variables refer to ones that are within the designers' control and noise variables to ones which are not. In a mobility network, one entity's noise variable could very well be another's control variable. With the links established between each of the stakeholders, the number of noise variables within the entire system becomes much smaller than the sum of the parts. For a revolutionary concept to maximize its probability of making a successful impact in the marketplace, the mobility network has to be calibrated for robustness as a whole system and not as individual entities.
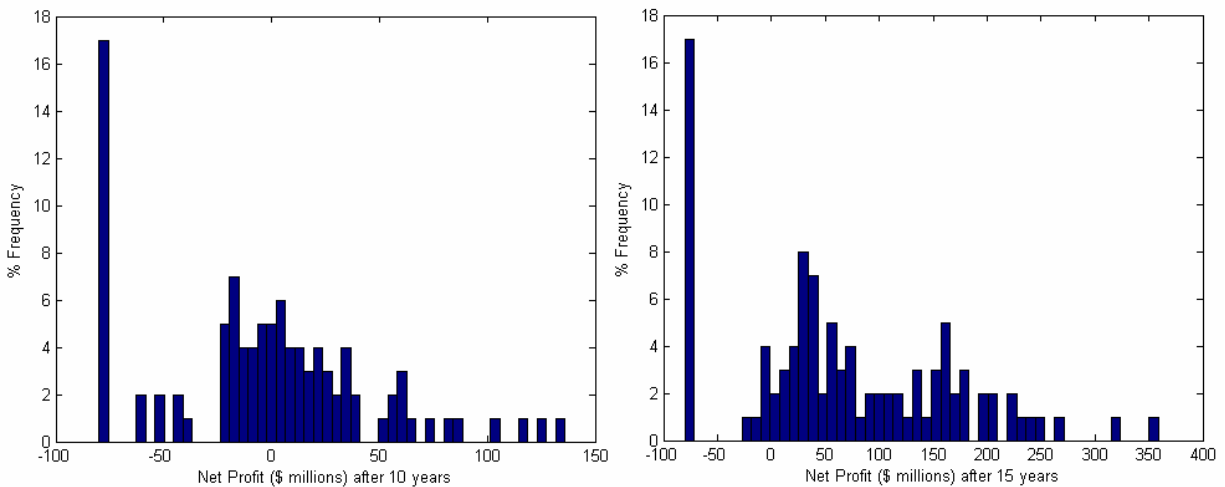

Figure 10 – Histogram of Net Profit after 10 and 15 years

Current Limitations and Future Work

The work described in this paper has been presented in two levels. First, a qualitative description of the mobility stakeholder network is discussed and then a quantitative analysis of the manufacturer's development cycle is presented. With the adoption of a top-down approach, depth in analytical modeling detail has not been achieved and is a future task at hand. Several future tasks, for the further development of the mobility dynamics environment, are listed below and in no order of importance.

- Use of Real Options theory to enhance the analytical capability of the manufacturer module. When an economic analysis is being undertaken to assess future viability of a design concept, a Net Present Value (NPV) approach, based on an assumed cash flow, is typically used to represent the value of the project. While such an approach is easily manageable with the aid of an excel spreadsheet and a dose of common sense, it is a deterministic method of calculating project value that is neither accurate nor realistic. A probabilistic enhancement to the

NPV approach includes ranges in uncertainty and provides valuable estimates of the probability of success. The value of a probabilistic approach, however, only lies in the ability to quantify the uncertainties involved. In order to account for the actions the project planner takes over time, in reaction to the fluctuations in the market, a stochastic model has to be employed. Real Options theory is derived from financial options theory and it is a stochastic method aimed at reducing the project's exposure to uncertainty.

- Use of Agent-Based methods and utility theory to formulate a consumer demand module. It would not be an understatement to designate the consumer demand module as the most important of the mobility stakeholder dynamics. Disruptive technologies are only viable on the assumption that consumer trends change with the introduction of new products, and prediction of future demand cannot be extrapolated from past product research data. With agent based methods, guidelines can be created that form the basis of consumer decisions and future behavior of consumer groups can be predicted.

- Creation of meta-models to represent other stakeholder entities. Through the use of response surface methodology, meta-models of the aircraft design module have been developed in the past [11]. The creation of similar meta-models for other stakeholder entities such as regulatory agencies and infrastructure providers remain a future modeling challenge. They will have to be based on existing high fidelity analysis tools and with sufficient flexibility to link with other modules. These meta-models can then be used to analyze the solution space of the mobility network and optimize policy solutions.

- Exploration of the noise/control dichotomy and policies to coordinate overall system robustness. Prior studies relating to risk reduction have been conducted piece-wise, with robustness of an individual stakeholder or a project as the focal point. An important aspect of future research would be the expansion of these boundaries to examine robust system-of-system scenarios.

Conclusion

The concept of future vehicles for mobility improvement was first introduced along with the need for paradigm change in aircraft design. Instead of focusing on static vehicle requirements generated from case studies, there exists a need for designers to generate potential requirements for future transportation from a dynamic viewpoint. Based on the underlying concept of mobility, a network of mobility stakeholders with the most significant effect on the transportation system was identified. The coupling of relationships between the stakeholders, which are inherently causal effects, provides an effective platform for the implementation of System Dynamics methods. Due to the large scope of the overall mobility problem, focus on the development cycle was necessary for initial quantitative analysis. The stock and flow model describes the flow of products through its design and certification stage as well as the revenue flow for the manufacturer, which is dependent on available products in the market. The simulation runs examined the effect of design & certification lead time as well as the failure rates and found the lead time to have much more significant impact on the long term financial stability of the manufacturer. A simple Monte Carlo simulation exercise was also performed to simulate the effects of uncertainty within the model and only 44% (based on assumed uncertainty ranges) of the cases were found to produce a net profit of greater than $100 million dollars over a 15 year period. The System Dynamics model of the development cycle is relevant to the overall study of the mobility environment, by providing policy guidelines in the relationship between research agencies and manufacturers.

References

1. Christensen, C. M. *The Innovator's Dilemma*. Boston: Harvard Business School Press, 1997
2. Holmes, B.J., "Alternatives for Air Mobility," *Proceedings of the 2002 World Aviation Congress*, Society of Automotive Engineers, Warrendale, PA, Nov.
3. Himola, O., Helo, P., Ojala, L. "The Value of Product Development Lead Time in Software Startup," *System Dynamics Review* 19 (2003): 75-82
4. Coyle, R.G. *System Dynamics Modelling. A Practical Approach*. London: Chapman & Hall, 1996
5. Reinertsen, D.G. *Managing the Design Factory*. New York: The Free Press, 1997
6. Starr, P.J. "Modeling Issues and Decisions in System Dynamics," *TIMS Studies in the Management Sciences* 14 (1980): 45-59
7. Sterman, J.D. *Business Dynamics*. Irwin Mcgraw-Hill, 2000
8. Forrester, J.W. *Urban Dynamics*. Cambridge: The M.I.T. Press, 1969
9. Mavris, D.N. and DeLaurentis, D.A., "Methodology for Examining the Simultaneous Impact of Requirements, Vehicle Characteristics, and Technologies on Military Aircraft Design," *Proceedings of the 22nd Congress of the International Council on the Aeronautical Sciences (ICAS)*, Harrogate, England, August 27-31, 2000. Paper ICAS-2000-1.4.5.
10. Myers, R.H., and Montgomery, D.C., *Response Surface Methodology: Process and Product Optimization Using Designed Experiments*, John Wiley & Sons Inc., Indianapolis, IN, 1995.
11. DeLaurentis, D.A., Mavris, D.N., "Uncertainty Modeling and Management in Multidisciplinary Analysis and Synthesis," AIAA Paper 2000-0422, Jan. 2000.
12. Du, X. and Chen, W., "Efficient Uncertainty Analysis Methods for Multidisciplinary Robust Design", *AIAA Journal*, Vol. 40, No. 3, 2002, pp. 545-552.
13. Meyer, M.D. and Miller E.J., *Urban Transportation Planning: A Decision Oriented Approach*, 2nd ed., McGraw-Hill, New York, 2001.
14. Donohue, G.L. and R. Shaver, "United States Air Transportation Capacity: Limits to Growth Part I (modeling) and Part II (policy)," National Research Council Transportation Research Board, National Academy Press, Report Nos. 00-0582 and 00-0583, Washington D.C., Jan. 2000.