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Development Cycle Time Simulation for Civil Aircraft

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Chapter 1

Introduction and Summary

Cycle Time Reduction (CTR) will be one of the major factors affecting the future of the civil aerospace industry. This focus comes from a non-traditional aerospace perspective but it is ultimately the end reflection of the level competition in the aircraft industry. The major buyers of aircraft, airlines, and leasing agencies, have come to view new aircraft as commodity items. In its simplest form, the major buyers pick the least cost aircraft that meets their needs. To successfully compete in this type of market, aircraft manufacturers must minimize costs and pass a portion of those savings on to the buyers. CTR is one strategy used to move the manufacturing firm down the cost curve.

One approach for examining CTR strategy looks at its implementation. This is usually defined as being either process centered or manufacturing centered. The process activities are based on the application of up-to-date management and control theories (including information technology) about how to improve and/or accelerate operations, but as applied to the aerospace manufacturing industry. The manufacturing processes are those best practices implemented in the aerospace manufacturing industry. These can be thought of as either those initially derived from other industries and applied to the aerospace industry, or those organically derived to solve specific problems in the aerospace industry.

Implementation of CTR strategies may not produce future profits, but that does not mean the strategy is a failure. In fact, as the level of competition rises, it is one of the tools to maintain profits. The net effect may show up as constant profits as opposed to increased profits.

The airframe development cycle describes the production phases of civil aircraft from concept to delivery.[1] It is this cycle that will be analyzed for possible reductions and/or improvements. The proper view of this cycle is not a static one. The actual development cycle is fluid and dynamic. The definition of the production phases is somewhat arbitrary and overlapping. The phases of the development cycle actually exist in parallel for each individual aircraft, with the first five or six aircraft going through different phases simultaneously.

The development cycle of future large passenger aircraft is a critical determinant of the future success of the commercial aerospace industry. The typical current development cycle spans several phases lasting 4 to 8 years. One of the keys to

[1] The complete aircraft development cycle is composed of the airframe development cycle and the engine development cycle. The engine development cycle was not examined in this study. In this context, the term “development cycle” refers only to the airframe development cycle.

the continued development of the aerospace industry and its profitability is finding ways to shorten or improve this cycle.

NASA's analysis of the current development cycle is embodied in a coarse model. A more accurate and refined model is required to better assess the effect of new technologies on the aircraft development cycle.

Two approaches can be used in the design of aircraft development cycle. The first is to take the framework as it exists and examine methods and practices to improve that framework. This is known as the process-reengineering framework. The second involves designing a wholly new process from start to finish.

The ideas explored in this report are based on the first approach. The second approach holds promise, particularly as it pertains the development of other than conventional technology and/or other than subsonic aircraft. This is because the goal of reduction of development time by a factor of two may require radical redesign, rather than simply process improvement. This aspect is beyond the scope of this study and is not directly covered here, although some of the industry reduction practices are focused in this direction.

The goals of the present effort are to

- conduct a literature review focusing on the cash flow implications of faster cycle times;
- conduct and report the results of interviews with aircraft manufacturers regarding cycle time reduction efforts;
- provide a framework to measure the benefits of NASA programs to reduce cycle time; and
- implement an empirical model to obtain numerical estimates of likely NASA program effects on cycle time;

REPORT SUMMARY

The current NASA Airframe Development Cycle Time Reduction Goal is 50 percent by year 2022. This goal is not achievable based on the program analysis done by the LMI/GRA team. It may be that the program technology progress factors, as determined by the NASA experts, were understated. If that is not the case, then the current roster of NASA Cycle Time Reduction programs needs to be reexamined. Programs that duplicate the reductions of others should be replaced with programs that offer non-duplicative reductions. In addition, new programs targeting a specific part of the cycle can be developed, as well as developing programs based on implementing best standards and practices.

In economic terms, the conventional view is that the industry has evolved into a duopoly, with Boeing competing against Airbus. This view must be modified somewhat, when considering certain segments of the industry; in particular, the growing demand for regional jet aircraft has led other smaller firms to enter the market. Market demand and cost characteristics for the regional jet market are quite different than those for larger aircraft, and so the characteristics of the design cycle may also be different. The duopoly characterization is appropriate for this segment of the market examined in this study, the larger (more than 100 seats) commercial aircraft.

Four major target areas of cycle time reduction efforts over the next several years are

- reducing engineering man-hours;
- reducing tooling hours;
- reducing test activity; and
- implementing process and information technologies.

Learning economies are an important aspect of realizing the benefits of cycle time reductions. In turn, this affects production costs and economic profits. These learning economies depreciate over time when they are unused. Therefore, it is important for a firm to maintain a constant or increasing rate of production over time in order to benefit from the decreased unit costs resulting from learning economies. This means that even small variations in production rates (especially in early years) can have dramatic effects on realized learning economies, and hence on net profits. This has several important implications for reductions in design cycle times.

Getting to market earlier means that the company will have more opportunities to dominate a particular market segment before a competitor can react. If a company can lock in more customers, it has a better chance of both producing more units and smoothing the production run over the product's life cycle and thereby realize its learning economies. By getting to market faster, the forecast for the product and the expected profitability of the program are more likely to be realized.

For the manufacturers, the benefits of airframe development cycle time reduction are fundamentally in the unit of dollars. The benefits are enumerated as increased sales, increased market share, and lower costs, best translated to dollars.

For NASA and the general public, the benefits are neither as direct or concrete, as their benefits are those derived from the manufacturers successful implementation of a CTR program. At the primary level there are technologies implemented by the manufacturers that can modified and transferred other industries. In addition there are the standard benefits derived from a healthy civil aerospace industry: additional aircraft sales, additional manufacturing, and airline industry employment, and the subsequent economic ripple effects. The secondary effects include the introduction of new aircraft and replacement of old ones. These effects are reduced air and noise pollution and added safety in the commercial fleet.

Report Overview and Structure

The remainder of this report is divided into six sections:

- Chapter 2 provides a review of basic economic theory relevant for the aircraft manufacturing industry. It discusses changes in market structure in the industry over time and reviews the competitive implications of reduced cycle time.
- Chapter 3 discusses the NASA modeling strategy for airframe development cycle analysis developed in 1998. This is followed by a discussion of manufacturer comments on the NASA model design that resulted from interviews undertaken with two major aircraft design groups. This chapter also includes a review of design cycle innovations implemented during the Boeing 777 aircraft program, as well as an overview of the likely targets of future reduction efforts by aircraft manufacturers.
- Chapter 4 discusses new economic evidence on the nature of learning economies that may have direct implications for the benefits of reduced cycle time in the commercial aircraft industry.
- Chapter 5 provides a theoretical framework for measuring the benefits of NASA program efforts to reduce cycle time.
- Chapter 6 discusses NASA's Tailored Cost Model (TCM) and describes LMI/GRA efforts to expand the model to allow for time dynamics. A detailed analysis of the underlying model structure is provided along with a description of the design cycle timeline that was implemented. This is followed by a discussion of how the revised model was then used to measure design cycle benefits of current NASA research programs.
- Chapter 7 presents a summary and conclusions, along with recommendations for possible future avenues of research and analysis.

Chapter 2
Literature Review

INTRODUCTION

This section presents the results of two literature reviews: one involving the market structure of the aircraft industry and the other regarding competitive implications of cycle time reduction.

The Commercial Aircraft Industry: Market Structure and Incentives to Invest[1]

The structure of the commercial aircraft industry can be characterized as having a relatively high degree of horizontal concentration, but a lack of vertical integration. Horizontal concentration describes the number of firms participating in the market at any one stage of production (e.g., airframes or engines). Vertical integration refers to the extent to which single firms participate in the market at several stages of production (e.g., a firm producing both airframes and engines is vertically integrated).

FIRM SIZE AND MARKET SHARE

Empirical evidence suggests that both firm size and seller concentration affect research and development (R&D) efforts. Specifically, the evidence suggests that increases in firm size resulted in proportionately greater levels of R&D effort; beyond the threshold point (about $400 million in sales in 1978 dollars) however, further increases in firm sales caused diminished levels of R&D. As shown in Table 2-1, all the major civil transport aircraft manufacturers are well beyond this size threshold.

Similarly, increases in market concentration tend to result in proportionately greater R&D efforts to be undertaken. Again, this effect diminishes at some point. However, the evidence is relatively weak on both accounts. Accordingly, our conclusions should be viewed with this in mind. The commercial aircraft industry largely exceeds, the threshold points for both firm size and market concentration. Table 2-1 shows recent market share data for large transport aircraft. The three largest airframe manufacturers, Boeing, McDonnell-Douglas, and Airbus, for example, had deliveries of civil jet transports valued at $31.2 billion, $2.7 billion

[1] With minor editorial changes, the following section is taken directly from parts of a report completed by GRA, Inc. under subcontract to Science Applications International Corporation, prepared for NASA Headquarters, “Economic Analysis of Aeronautical R&T: A Survey,” November 1999.

and $12.8 billion, respectively in 1998.[2] As shown in Table 2-1, the market share of just the largest commercial airframe manufacturer, Boeing, exceeds 70 percent of the market for large aircraft in dollar value, counting both Boeing and McDonnell-Douglas. Thus, by both standards, the industry is far past the optimal threshold points conducive to R&D activities. Because of this, and in view of the inconclusive evidence regarding the general effects of firm size and market share, these aspects of market share are not likely to mitigate the appropriability problems facing the industry.

Table 2-1. Large Transport Aircraft Manufacturer Deliveries and Market Shares

	Deliveries (dollars-billions)								
	1990	1991	1992	1993	1994	1995	1996	1997	1998
BOEING	$20.4	$21.5	$22.8	$19.0	$15.3	$12.5	$15.2	$22.2	$31.2
DOUGLAS	3.7	6.2	6.0	4.4	2.5	3.0	2.8	2.7	2.7
AIRBUS	4.4	7.1	7.1	8.0	7.9	8.9	8.2	10.8	12.8
TOTAL	28.5	34.8	35.9	31.4	25.7	24.4	26.2	35.7	46.7
EUROPE	15.4%	20.4%	19.8%	25.5%	30.7%	36.5%	31.3%	30.3%	27.4%
USA	84.6%	79.6%	80.2%	74.5%	69.3%	63.5%	68.7%	69.7%	72.6%
BOEING	71.6%	61.8%	63.5%	60.5%	59.5%	51.2%	58.0%	62.2%	66.8%

Product Diversity

Diversified firms producing products in closely related markets may have added incentives to conduct R&D because the benefits can be spread over several products. The existence of a large military market aids the industry in spreading the costs of the common military/civilian R&D base. But, the key question here is whether the existence of the military market causes firms to undertake civilian-oriented R&D, speculating that the results can be applied in the military sector. While this effect may exist, it is likely to be small. Military and civilian hardware tend to be quite different in performance characteristics, with military applications usually preceding civilian use.[3] Disembodied technologies—new concepts or knowledge—may be applicable in either sector, but the production of such R&D will be subject to the appropriability problem, regardless of its eventual use.

Increasing Returns to Adoption

Another important point is that firms will have an incentive to invest in existing technology when increasing returns to adoption are present. This can delay or prevent the introduction of a new superior technology. Increasing returns can be

[2] McDonnell-Douglas merged with Boeing in 1997.

[3] Some knowledgeable observers say that the military now benefits from innovations first applied in the civil arena.

present when there are large learning curve effects on production costs (i.e., the incremental production costs decline with succeeding units of production). A firm has an incentive to produce more of an existing design, rather than introduce new technology that would cause higher costs associated with the beginning of the learning curve.

The increasing returns to adoption model may be particularly appropriate for the civil aircraft industry.[4] Here a manufacturer is often faced with a choice of producing a derivative of an existing design versus a totally new aircraft. (Boeing is facing this decision today with plans for a large, long-range aircraft to compete with the large transport being considered by Airbus, the A-3XX. Boeing is determining whether to stretch the B-747 or undertake a new design.) The implications of the increasing returns to adoption case are that firms may have economic incentives to forego superior technologies that may have potentially large long-run payoffs. As a result, firms may underinvest in R&D, even up to technology demonstration and validation. As noted in the next section, this does not apply to cases where companies receive development funds from government. If government wants industry to apply these superior technologies, it may have to invest in their development, demonstration, and validation. This is especially the case for technologies that are significantly different than those embodied on existing products. The technology base for high-speed civil transport aircraft is one example of potentially superior technology in which the industry may not have adequate incentives to invest.

OTHER SOURCES OF R&D

This discussion has intentionally focused on privately funded R&D. Considered here are incentives private firms in the industry would have to fund R&D that is currently derived from other sources. In general, the types of R&D provided by other sources are, by their very nature, less appropriable than privately conducted R&D, which is dominated by applied research and development activities. Consequently, private firms in general will have even less incentive to conduct R&D currently derived from other sources.

An important question for the present analysis is: To what extent will private firms have incentives to conduct R&D currently performed or sponsored by NASA? As an R&D source, NASA makes contributions to the industry's technology base in terms of infratechnology,[5] and discipline and applied research. Relatively little private expenditure is devoted to these elements of the technology base. The reasons for this phenomenon are twofold:

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[4] Arthur, op cit, p. 116.

[5] Infratechnology includes both methods and basic data (e.g., test methods, computational procedures and materials characteristics) for conducting or using other types of research and technology.

- Private firms have less incentive to conduct discipline (or basic) and applied R&D because of the problems of appropriability (as well as the risk and payback period problems).

- Neutral technology can be obtained from other sources.

The latter point, is the central policy issue. Given the previous discussion on the appropriability of neutral technology and the results obtained from the economic model of the market for R&D, it appears that the private market will not respond well to the burden of undertaking R&D activities currently conducted by NASA.

A second issue, whether NASA sponsored R&D conducted by private firms, is a complement or a substitute for privately financed R&D. The concern here is that NASA (or government) sponsored R&D "crowds out" R&D that otherwise would be financed and conducted privately. A priori expectations lead one to believe that the crowding out effect is not substantial: NASA typically sponsors projects that exhibit scientific potential rather than short-term commercial potential. In addition, there is empirical evidence that the crowding out effect is minimal. One study, which focused specifically on the transport industry, estimated that each dollar of government sponsored "mission-oriented" research reduced privately sponsored research by only 8 cents.[6] Recall that the discussion above of absorptive capacity indicates that public R&D could stimulate private R&D investment.

NASA-SPONSORED R&D: RISK AND THE PAYBACK PERIOD

Appropriability is not the only factor considered in a firm's decision to invest in R&D. Specifically, both the level of risk associated with a project and the duration of the payback period influence the investment decision, even when appropriability is not an issue. Development activities are least risky and have, in general, the shortest payback period, while investments in discipline research and infratechnology are generally most risky and have the longest payback periods.

Regarding the risk and payback period problems, the important issue here is: Does the type of R&D conducted by NASA complement R&D that private firms tend to conduct, or are NASA R&D activities substitutes? As noted above, many of NASA's resources are devoted to basic research and the development of infratechnology. These activities complement the efforts of the private sector since they are risky and tend to have long payback periods.

NASA also sponsors and conducts applied research. Although this type of R&D investment is generally less of a problem in terms of risk and the payback period, it is less desirable to private firms than development activities. Moreover, applied

[6] J. Carmicheal, "The Effects of Mission-Oriented Public R&D Spending on Private Industry," *Journal of Finance*, 36, (1981), 617-627.

research in aeronautics, particularly the type that NASA conducts, often requires the extensive use of large-scale facilities. If the burden of conducting these projects were placed on the private sector, substantial duplication of both large-scale facilities and expensive experiments may result.

EXTENSIONS

There are two additional features of the industry that play an important role in research and development. These features address the following issues:

- The monopsony buying power that sometimes is vested in airlines as a result of direct competition between aircraft manufacturers.
- The role of the dominant firm and its effects on competition and technological change.

These two facets of the commercial aircraft industry are considered below.

Monopsony Power of Airlines

Because aircraft manufacturing requires high development costs, the industry is often compared to other industries with high development costs (e.g., automobiles, semiconductors and so forth). The key distinction is that aircraft are built in small numbers and, in fact, are custom-built to airline specifications. Stability in the marketplace depends upon the ability of firms to differentiate their products and, more specifically, to build different size aircraft with different capabilities that will be attractive to specific niches in the marketplace. When firms build aircraft of the same size with similar capabilities, they often find that the market is too small to yield satisfactory returns on their investments.[7] Competition becomes so vigorous for limited sales opportunities that airlines acquire monopsony power—the ability to dictate the terms of the sale to the seller. This situation can have debilitating effects on competitors and it can reinforce the already existing tendency for one firm to emerge as the dominant competitor during any given era.

The Effects of a Dominant Firm

Firms become dominant in the industry when they have been successful in making significant technological leaps forward. Boeing's dominance over the past 25 years can be directly traced to its introduction of the 707, which, although not the first turbojet introduced, was the first to combine both speed and cost savings for

[7] The classic examples of this are the DC-10 and L-1011. Both targeted the same market niche in range and size. Losses on the L-1011 forced Lockheed to withdraw from the civil aircraft manufacturing industry.

its operators. Similarly, the DC-1-2-3 series dominated airline fleets worldwide in the 1930s. The DC-3 combined advantages of speed, size, range, and cost.

What is most significant about these two success stories is that both Douglas in the 1930s and Boeing in the 1950s were minor competitors in the commercial aircraft business when they undertook their projects. In fact, the DC-1-2-3 series was the first transport aircraft Douglas ever built. History suggests that dominant firms in the airframe industry will be reluctant to make technological leaps forward because they do not wish to compete with their existing and successful product lines and their incentives to undertake the considerable risks involved are less than those of companies with less of a stake in the existing aircraft market.

In other words, dominant firms become dominant by successfully making significant technological breakthroughs first. They remain dominant by winning any direct competition with other major manufacturers (e.g., the B-707 vs. DC-8, and the DC-3 vs. the B-247) and by successfully differentiating products (e.g., the B-727 and the B-747). But they can lose their dominance by underinvesting in technological advances and the R&D necessary to support them.

It should be stressed that incorporating a major technological advantage is no guarantee of success. The de Havilland Comet, the Vickers V-1000, and the Concorde are examples of failed attempts by competitors to make the technological breakthroughs that could have led to market dominance.

In reviewing those histories of major technological breakthroughs, it is important to recognize the role played by externally generated technology. The DC-3 incorporated a number of innovations first developed elsewhere: the NACA cowling; all metal, stressed monoplane structures; and variable pitch propellers (invented in 1871). The inability of the original investors to appropriate all of the benefits of the technologies made the DC-3 possible. Likewise, the KC-135/B-707 was based on Boeing experience with the B-47 and B-52, both military aircraft.

The findings concerning the incentives of dominant firms to underinvest in major technological advances and the R&D necessary to support them is consistent with the economic literature. A brief summary of that literature indicates the following points:

- Some concentration in an industry may be conducive to invention and innovation because the firms will have sufficient financial capabilities to undertake these activities and because they have an incentive to differentiate their product and thereby earn some monopoly profits; but,

- High concentration (the case of the dominant firm) can retard progress by restricting the number of independent initiatives and by dampening the incentives of other firms to compete.

- The key to preserving effective competition in less-than-perfectly-competitive industries is to keep entry barriers sufficiently low so that newcomers can enter or threaten to enter.

- Access to radical new technologies (and the complementary technologies to support them) is a key to preserving low entry barriers and competition especially in high technology industries.

RISK IN THE COMMERCIAL AIRCRAFT INDUSTRY

The commercial aircraft industry must contend with rapidly advancing technology and costs. There are innate risks associated with developing and producing airframes incorporating new and often untried technology. The emphasis on research and development in the airframe industry is a two-edged sword with respect to financial risk: It is costly and the returns from R&D are highly uncertain.

Earlier, it was noted that risk could be mitigated if a firm could diversify its activities into several relatively small projects, even if the total level of R&D is relatively high. On the other hand, if the nature of the industry is such that R&D diversification is infeasible, then the risk problem becomes more significant.

The nature of the commercial aircraft industry is such that very large single R&D projects must be undertaken. Development costs for the Boeing 747, for example, have been estimated at $1.2 billion spanning roughly a 4 year period between December 1965 to January 1970.[8] At the time the development of the aircraft commenced in late 1965, total shareholder's equity was only about $372 million.[9] The ratio of development costs to equity was approximately 3.23; that is, the development cost of the B-747 alone was more than three times the value of stockholders' investments. In short, Boeing was required literally to "bet" the company on the success of the B-747. (It was recently reported that the development costs for its planned 600-800 seat aircraft would be more than $10 billion.[10] The development costs for the Airbus A3XX is projected at $12 billion by 2004).[11]

McDonnell-Douglas incurred similar risks in developing the DC-10. Development costs for this aircraft have been estimated at $1.1 billion.[12] The value of shareholders equity was only about $364 million in 1967, the year in which development commenced.[13] The ratio of development costs to equity was about 3.02. McDonnell-Douglas then, was also required to risk the fate of the firm in developing the DC-10.

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[8] RADCAP, op cit, Appendix 9, p. 21.

[9] Boeing Annual Report, 1966.

[10] Laurence Zuckerman, "The Jet Wars of the Future," *The New York Times*, July 9, 1999, p. C5.

[11] Reuters News Service, New York, Feb. 2, 2000.

[12] RADCAP, op cit, Appendix 9, p. 21.

[13] McDonnell-Douglas Annual Report, 1967.

SUMMARY AND IMPLICATIONS

Access to non-appropriable technologies from other sources (e.g., NASA) appears to be critical to the maintenance of efficient production of civilian transports for the following reasons:

- Firms in general have a tendency to underinvest in R&D, for all the reasons cited above.
- The existence of dominant firms tends to impede technological progress and competition.
- The financial capacity of aircraft manufacturers is sometimes debilitated by the monopsony power of airlines.
- Aircraft manufacturing firms already face substantial risks relative to other manufacturers. The industry is not likely to be able to respond well to the burden of accepting additional risky R&D projects.

Cycle time reduction has traditionally been associated with decreased costs and improved customer satisfaction. There are other factors that are equally important when analyzing the airframe manufacturing industry. These would include a faster time to market, as well as increased market share and reduced total operating costs of the aircraft. These factors all have one thing in common, they lead to higher corporate profits.

The importance of cycle time reductions in capital intensive industries represents a fundamental strategic shift. Historically the major barriers to entry and protector of profits in this industry segment have been economy of scale, which was a function of capital intensity. Advances in computer technology, manufacturing, and, in some sense financing, have made economy of time a method to compete with economy of scale.

The general theory states that competitive firms have an incentive to invest in cost savings processes more than a monopolistic firm does. But the degree of competition is inversely related to the potential profit. Those firms with the highest degree of competition do invest, but they do so to lower costs and stay in business as opposed to extracting more profits.

Furthermore, when examined at the duopoly level, the general theory holds that two firms competing in an industry with no entry will continue to innovate (or imitate) when the cost of innovation (imitation) is less than the benefits, despite the fact that the other firm can benefit without incurring costs. This is because profits are still being made in the industry, although the marginal rate of profits may be declining. Firms will accept a lower rate of return rather than lose customers to the competitor.

The level of competition will determine both the degree and type of innovation to occur. But even more important, it will also determine the time length in which any innovation serves as a profitable degree of differentiation before it is converted to a standard readily available attribute. Theoretically at the extremes, this time span is zero under perfect competition and infinite in a monopoly. In real life we see competitive advantages lasting as little as 6 months in the computer industry, to 1 to 3 years in the auto industry. Using those industries as the time scale, a competitive advantage in the airframe industry should be currently expected to last 2 to 4 years before it is rendered as standard.

So cycle time reduction should be expected to occur. All firms will attempt it. One firm will succeed faster than the others. That competitor will have a temporary competitive advantage, until another firm catches up. At that point the innovation becomes standard and the search is on for a new innovation.

Chapter 3

Models of Aircraft Development Cycle Theory and Practice

THE REVISED NASA 1998 DESIGN AND DEVELOPMENT CYCLE FOR AIRFRAMES SYSTEMS ANALYSIS

In 1998, NASA produced a draft final report outlining a modeling strategy for airframe development cycle analysis. As noted in that report:

> "The single greatest liability in building a capability in vehicle development cycle analysis is the lack of publicly available historical (empirical) information. In addition, the decisions regarding how the process for a new design should be structured are extremely subjective. Together, these factors lead to a very blurred story from industry both on how they conduct design today and how design is envisioned in the future. This blurred information embodied the available data upon which to build a model for development cycle analysis." [1]

With this and other caveats, the NASA report cited two primary data sources used to develop the modeling outline described in the report. One was a Boeing paper produced as a deliverable to an AST contract involving integrated wing design.[2] The second source was a set of published reports regarding the development schedule for the Boeing 777 aircraft.[3] As is made clear early on in the NASA report, information derived from the 777 program is more relevant for new, as opposed to derivative, design cycles.

The NASA model of design cycles is broken down into five sequential phases:

- Early configuration and market analysis
- Product definition
- Detailed structural, systems, and process design
- Fabrication,assembly, and testing

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[1] NASA Systems Analysis Branch, ASAD, "Final Report on MOASS 98 Airframe Development."

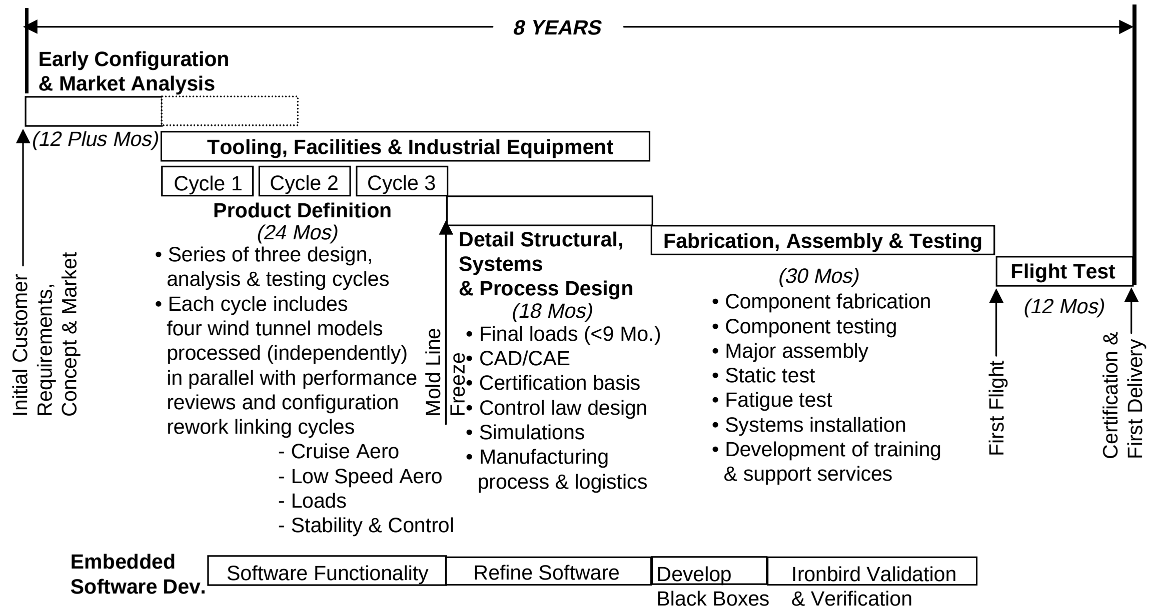
[2] NASA Contract NAS1-20267, presentation for Task 10.

[3] See Footnote 1 citation, Section II.

- Flight testing.

The timeline is shown in Figure 3-1. Each of these steps is discussed in more detail below.

Figure 3-1. 1990 State-of-the-Art Airframe Development Cycle



Early Configuration and Market Analysis

The key element in configuration and market analysis is to identify customer and product needs. There is an important interaction between customer airline needs and the manufacturer's product lineup. Both Boeing and Airbus have a lineup of products that reflect the large up-front capital costs involved in designing, testing, and manufacturing a jet aircraft. Because of these large expenses, a small number of designs form the basis for the derivative aircraft types offered by both manufacturers. Both companies offer a large number of variants from these base designs with differentiated product characteristics (range, speed, fuel economy, seat and cabin space, etc). The primary purpose of the market analysis phase is to identify needs of potential customer airlines and whether they can be met with current products, variants of these products, or if a new aircraft design may be required. This determination is crucial due to the extreme variation in design cycle time and costs for new aircraft designs versus derivative ones.

During this phase, design and tradeoff studies may be used to identify basic range and/or payload parameters. In addition, potential market size, likely customers, and price ranges may be analyzed. In turn, these analyses will depend on projections of air travel demand, current fleet sizes, and offer prices of other existing aircraft. An increasingly important aspect of this analysis phase for both Boeing and Airbus is the competitive analysis of the other companies' potential product offers and/or plans. In this model, the market analysis phase is assumed to take up the first 12 months of the development cycle.

Product Definition

The product definition phase contains all of the preliminary design and other work needed to develop a fixed mold line. For modeling, the NASA report identifies three consecutive design/wind tunnel cycles, each of which is assumed to take approximately 8 months. At the end of each cycle, the design strategy may be revised. It eventually converges to an acceptable design at the end of the third cycle. Each cycle is assumed to consist of four parallel wind tunnel models that go through design and testing. Aircraft models are built and tested for

- high speed aerodynamics (cruising);
- low speed aerodynamics (takeoff and landing);
- stability and control tests; and
- load tests.

The NASA model defined a detailed design structure matrix to capture the integrability of the four phases of wind tunnel testing. This matrix is described in detail in the ASAD final report. As noted above, the NASA model assumes three consecutive wind tunnel cycle models. As noted in the NASA report, Cycle 1 is assumed to typically fail to meet performance or handling objectives. Cycle 2 meets performance objectives but fails handling objectives. Finally, Cycle 3 meets both performance and handling objectives.

Detailed Design

The detailed design phase contains all of the design work needed to go from a mold line to cutting metal. The primary driver in this phase is the creation of manufacturing drawings and data sets and their interrelationships, which entail detailed structural analysis. In practice, the detailed design work is broken out by major aircraft systems, for example:

- Fuselage
- Wings
- Landing gear/tail/rudder
- Flight controls (internals)
- Flight controls (surfaces and attachments)

- Fuel system
- Nacelle/pylons
- Electrical system and wiring
- Cockpit
- Cabin
- Auxiliary power unit
- Fixed equipment
- Environmental controls
- Engines
- HVAC.

The detailed design phase is assumed to take 18 months and involves the extensive use of computer aided design and engineering functions, repeated simulation analyses, analysis of various manufacturing, process, and logistics issues, certification issues, and determination of final load designs.

Fabrication, Assembly, and Testing

This phase of the design cycle involves component fabrication, major assembly, testing (both static and fatigue), systems integration, and development of training and support services. New designs may also require the construction of new tooling facilities and equipment, and derivative designs may require changes in current tooling and equipment facilities. For modeling, this phase was assumed to take 30 months, although clearly the actual time consumed will depend importantly on whether the design is new or derivative. As an aside, it should also be mentioned that floor space requirements might become an important issue in this phase depending on the wing span and other size characteristics of the aircraft under development.

Clearly the fabrication and assembly steps are important aspects of this phase that may serve as bottlenecks before certain types of testing can be started; however, certain system functionality testing work can be done before fabrication is complete. In addition, it is important to note that for certain aspects of ground testing, actual physical checks for defective parts or other shortfalls must be completed. For these purposes, computer simulation is not appropriate. Another important aspect of this phase is the integration of various aircraft systems. Much of the testing for systems integration may be carried out by third party manufacturers; however, they are typically verified by an in-house systems integration laboratory

(SIL). Test airplanes may be developed for static, fatigue and/or flight testing. Those that undergo flight testing are eventually sold to customers.

Another important aspect of this phase involves certification testing, which includes type certification (e.g., valid FAR Part 25 certificate), insurance that production manufacturing processes produce aircraft that conform to technical drawings, airworthiness certification, airline certification, and flight crew/cabin crew certification.

The fabrication, assembly, and testing phase is assumed to take approximately 30 months in the NASA model. This may include the development of several test aircraft in preparation for flight testing.

Flight Testing

The key elements of this phase involve the validation of performance estimates, exploration of the flight envelope, and certification flight tests. Typically, computer simulation cannot be used on new aircraft for certification purposes. However, some derivative designs can be certified with the aid of computer simulation. In addition, certain engine certifications can be completed in wind tunnel testing. This phase ends with the modification and delivery of the first airplane to a customer. Again, flight testing depends importantly on whether the design is new or derivative.

Summary

Table 3-1 summarizes the approximate costs by design cycle phase for a new design product. Typically, early configuration and market analysis costs are not attributed to a specific product. They are viewed as activities that measure market needs and can lead to product development.

Table 3-1. Percentage of Cost By Design Cycle Phase—New Designs

Phase	Percentage
Early Configuration and Market Analysis*	
Product Definition	10
Detailed Design	30
Tooling, Facilities, and Industrial Equipment	20
Fabrication, Assembly, and General Testing	30
Flight Testing	10
	100

*On-going activity that occurs before authority to proceed.

MANUFACTURER COMMENTS ON THE BASE CASE NASA MODEL DESIGN

The study team participated in interviews with two major aircraft design groups to confirm and refine the design cycle elements and times used in the base NASA model. The interview questions are contained in Appendix A. For confidentiality, the actual responses are not included in this report, but were used throughout the study and are embedded in this report.

These interviews essentially confirmed the validity of the basic structure described above, although both sources emphasized that each aircraft design is unique and so it is quite difficult to specify a generic model that would be appropriate for any particular design.[4] In addition, the magnitude and span of each model component may vary with the size of the vehicle being developed and the amount of new design required. Entirely new programs may require large investments at each step and longer development times. In derivative programs, certain steps in the generic model may have to be lengthened or adjusted, while others may be curtailed substantially. For example, facilities from an older design may be reusable during the design process of a derivative aircraft (although tooling facilities and/or other machinery tends to wear out over time).

The regulatory environment continues to change, and this can have differential impacts on different programs. For example, the Boeing 777 program included an objective of achieving ETOPS certification concurrently with FAA certification. This required dramatically more test flight activity than would otherwise have been the case. Sources indicate that ETOPS added approximately 2,000 flight hours to the test flight program.

In addition, manufacturers may have to contend with both FAA and JAA (European) regulators whose certification requirements can vary from each other. For example, JAA requirements regarding escape hatches on some of the derivative Boeing 737 programs required extensive redesigns that added several months to the design cycle process.

A general theme common throughout the interviews was that the design cycle is entirely different for new products as opposed to derivative ones. The time from early configuration and market analysis to first delivery has typically spanned from 6 to 8 years for entirely new designs, compared to 28 to 40 months for derivative products. Development costs of a major derivative can incur nonrecurring costs of 75 percent of those of a new design while for a relatively minor derivative, the costs can be from ten to 25 percent of a new design.

[4] One of these design groups played a role in developing the base NASA model so it is not surprising that it corroborated its earlier work.

Early Configuration and Market Analysis

The early configuration and market analysis phase is one that manufacturers almost always are active in. Only some of these efforts lead to product launch decisions. These mostly involve analysis and studies carried out by market research, preliminary design and competitive analysis staff. One manufacturer maintains almost a constant dialogue with the largest airlines; however, the level of resources dedicated to this activity is not large when viewed in the context of the costs to develop a new aircraft.

A key milestone in any design process is the issuance of an authorization to proceed from the manufacturers executive decision-makers. While the NASA documents we reviewed do not specifically discuss it, a key element in the pre-ATP timeframe is the development of a product specification document. Such a document describes the configuration that is to be offered for sale and defines the aircraft's performance characteristics. An essential part of the sales offer is the issuance of performance guarantees. The product specification document, if successful, should lead to the emergence of a firm customer consensus about the need for and product characteristics of the aircraft to be produced.

When the product specification is complete, company decision-makers may then grant an Authority To Offer (ATO), which is needed to obtain credit financing for the large development costs that will be expended prior to first delivery.

With the product specification document completed, ATO granted, and financing arranged, sales personnel then could begin to attempt to "sell" the product to potential customers. Finally, only after a certain predetermined number of units are "sold" can Authority to Proceed (ATP) be approved by top management. In many cases, ATP approval is based not only on the number of units sold, but also on the number and identity of launch customers. For example, firm orders from a leading carrier obviously carry more weight than soft (optional) orders from lesser carriers. Once official ATP approval is given, the program is officially launched and the "hard" design cycle activities begin.

Clearly, customer and product needs are essential issues that have to be satisfactorily addressed before the rest of the design cycle can be pursued. The manufacturers must deal with marketing, finance, engineering and flight operations groups at potential customer airlines. Often airline performance needs are stated in terms of critical city-pairs in their route systems that must be served without payload degradation on most days.

Again, the time and effort devoted to this phase is very dependent on new versus derivative designs. However, the manpower, analysis and studies that go into these analyses involve relatively minor costs as compared to the funds expended during the rest of the design cycle. For the largest airline, the aircraft manufacturers are essentially in the marketing and early configuration phase on a continuous basis. For these reasons, the NASA systems study model can safely treat this phase as a fixed block of time with little or no reduction in the time or cost expended.

Product Definition

One aircraft design group believes that product definition is the formal start of a new or derivative aircraft program. As described earlier, the NASA model identifies three consecutive design cycles in this phase, each lasting an 8-month period. This sequence is roughly accurate, for example, for the Boeing 777 program, but for derivatives, there may be no essential need for three cycles, and on unconventional or new kinds of vehicles (High-Speed Civil Transport, Large Blended Wing Body) there may be a need for additional cycles.

Variability in the 8-month iteration schedule is probably significant and reasons for expansion or compression arise in real time and are dealt with as they occur. Within each cycle, the NASA model specifies four parallel wind tunnel models that go through design and testing. The manufacturers indicated that the wind tunnel activities generally are in fact operated independently, and may involve different model scales and geographically separate tunnels. It is the high lift cycle test that is critical for the models to pass in order for the program to proceed further.

The manufacturers also indicated that in the future there likely would not be a need to conduct three consecutive wind tunnel cycles. Instead, elements of the cycle will be staggered along with mold line release for different parts of the aircraft.

As for cost parameters, it was estimated that the product definition phase probably consumes one-quarter to one-third of total engineering costs. The cost of tunnel operation varies somewhat based on tunnel size and site capabilities, but from a larger perspective, wind tunnel activities themselves probably represent less than 3 percent of the total development cost.

Manufacturers believe that significant opportunities exist in this phase for reductions in cycle time and cost. The replacement of physical tests with virtual (computer-based) tests is regarded as the primary way to reduce times and costs in the future. However, a leading concern is the issue of liability in accidents or failures. Recent Delta III launch vehicle failures suggest that a reliance on virtual testing has some risks.

In general, low speed testing, loads testing, and simulation are the focus of the manufacturers current cycle time reduction efforts. The goal is to produce faster wind tunnels, pressure sensitive paints, faster data reduction, and process improvements, including changes in management style and processes. For low-speed design, one goal is to extend computational fluid dynamics (CFD)-based testing and analysis from cruise mode to other activities. Overall, one design team believes it could reduce time in the product definition phase by 50 percent over a full-year period.

Detailed Design

Aircraft manufacturers have traditionally broken out the detailed design work into sections of the aircraft, along the lines described earlier. The fuselage, wing, and tail structures are further subdivided into smaller sections. There are many manufacturing limitations in detailed design work that significantly affect design time and costs. These include supplier availability, required sizes of aluminum sheets, hangar sizes, airport limitations, and transportation parameters such as the turning radius of railway track and the size of railway flatbed cars. The manufacturers suggested that the cockpit, wings, and horizontal tail typically take the longest to design and are the most expensive elements.

It is in the detailed design phase where systems integration becomes critical. All engineering disciplines participate in the integration process and initiatives suggested for streamlining the preliminary design are applicable at this point as well. The systems integration process includes not only the integration of the various components of the aircraft, but also consideration of factory layout options. As with the other phases of the development cycle, the time and cost associated with detailed design varies from program to program, and may be quite different for new designs as opposed to derivative ones.

The manufacturers are making significant efforts to incorporate component commonality in various sections of the aircraft, so that some component designs can be reused across programs. Significant efforts are being focused on cockpit and maintenance commonality. In addition, parametric computer aided design techniques are being implemented to enable derivative designs to be mixed on the same line. With these sorts of efforts, the manufacturers hope to garner significant time and cost reductions over the next 5 to 10 years.

The manufacturers are also investing heavily in knowledge-based engineering (KBE) concepts. These techniques are being used to supplement traditional CAD-based automation to help shorten the design process. KBE incorporates both "generative modeling"—the ability to create engineering models that can in turn create other models themselves, and "total product modeling"—models that incorporate not only engineering parameters, but also financial and marketing criteria. Airbus has used knowledge-based engineering techniques in its design of the A340-600, a stretched version of the existing A340-300 aircraft. The KBE approach was used to design and analyze all of the rib feet used in the stretch A340 wing design. The rib feet are flanges used to bolt the wing skin to each rib that runs from the front to the back of the wing and stringer, along its length. Each rib foot is slightly different from its neighbor; using conventional CAD techniques would have taken approximately one full man-year to design and analyze all of the feet. Airbus developed software that itself was able to create the CAD model needed for the rib feet. The entire rib design for the A-340 wing was completed in less than one man-day.

Many of the improvements incorporated into this phase, such as laser-guided tools and computer aided design, show up downstream in reduced aircraft production costs. Overall, one team expects one-half of the costs for some activities in this phase could be eliminated over 5 years. Not all product elements—such as long lead-time items are susceptible to this level on cost (and time) reduction.

Tooling, Facilities, and Industrial Equipment Development

This is an additional phase cited by the manufacturers' interviewees that must be completed before the actual fabrication assembly and testing phase is begun. New tooling facilities and equipment are always required for new design, and because tools tend to wear out over time, refurbishments or replacements must be completed even for derivative designs. For example, Boeing noted that some of the 727 fuselage tools could be used for the 757 program, but at that point these tools were wearing out and many of them had to be replaced.

An important consideration here is the size of the aircraft under development. In particular, increases in wing span necessitate larger factory floor spaces. Also, it is interesting to note that Airbus has only two basic body cross-section designs, while for Boeing each aircraft is different.

Savings in setup times and more efficient use of floor space are short-term goals that the manufacturers hope to achieve within the next 5 years; the company has a goal of reducing floor space used in production by 10 percent in 1 year and by 20 percent in 5 years. In addition, efficiencies may be gained from the use of adaptive tooling, laser alignment and knowledge-based engineering. These subjects are being investigated at MIT under the Lean Aircraft Initiative Program.

Fabrication, Assembly, and Testing

As described earlier, this step includes component fabrication, major assembly, static and fatigue testing, and training and support services development. For modeling, the manufacturers noted that the fabrication and assembly components can be treated as recurring cost items while the static and fatigue testing, software development, and training and support services are nonrecurring cost items.

It should also be noted that a significant portion of software development is often conducted concurrently with hardware design and often has a longer time span. It should also be noted that additional tests for propulsion, avionics and fixed equipment systems are carried out during this phase as well. For new designs, static tests are often conducted on airframes where some non-essential or redundant components have been replaced by "mass simulations." Similarly, fatigue tests are often performed on discrete rigs for the wing, fuselage, and tail structures. Also, ground tests for derivative aircraft may be significantly curtailed relative to new programs.

A typical build of test airplanes may look like the following:

- Airframe No. 1—flight testing
- Airframe No. 2—flight testing
- Airframe No. 3—static testing
- Airframe No. 4—flight testing
- Airframe No. 5—fatigue testing
- Airframe No. 6—flight testing
- Airframe No. 7—flight testing.

Flight Tests

This phase typically involves several aircraft. Historically, the actual number of flight test hours has grown over time. This is partially due to the increased stringency of required FAA certifications and the corresponding growth in aircraft system complexity.

It is important to note that significant time can be expended in designing and installing the flight test instrumentation, as opposed to the flight testing itself. For example, the 757 and 767 had approximately the same number of test flight days but the 757's non-flying days were much higher due to additional ground support and documentation expenditures. One suggested rule of thumb was that a single test airplane could provide somewhere between 30 and 50 flight hours per month. Thus, if an entirely new design (non-ETOPS) were to require, say 1,800 to 2,000 flight hours to reach certification, this would entail approximately 40 aircraft months of test flying. With three or four aircraft included into the test program, the actual calendar time spent is approximately 1 year. The flight test span for derivative designs is currently on the order of 10 months for a typical program. Current goals are to reduce the time spent on flight testing from 12 months to 8 to 10 months for new designs, and from 10 months to 4 to 5 months for derivative designs. This could be accomplished by relying more on the observed performance of ground test rigs and the use of simulations in lieu of actual flight tests.

Review of Boeing 777 Design Cycle Innovations

Parts of the NASA generic model described earlier closely follow the design processes used in the development of the Boeing 777 aircraft. The 777 development program represented a significant departure from the company's traditional methods of design and development. In particular, the program included a new product definition process and an integrated time-phased test program.

The product definition phase of aircraft development is a major cost driver for manufacturing costs. In turn, a large portion of manufacturing costs are due to the recurring costs that result from changes in product definition necessary to correct part-to-part interferences. Traditionally, the identification of gaps between parts or part overlaps would require a long sequence of change activities, including fit-up, fastener redesign, description of the new part required along with part number, part definition and dimension, drawing clarifications, edge margin, and whole pattern definitions. The costs of these types of changes were traditionally quite high because they could come late in the development program and result in completely reworked parts and tools.

A revised product definition process was instituted for the 777 program based on a strategy of concurrent engineering and three dimensional digital product definition. Design integration was a key aspect of the 777 product definition strategy. To this end, the design phase was broken into six stages:

- Initial concepts—This included test requirements, firm structures configuration and a preliminary tooling plan
- Concept development—Preliminary loads and systems interfaces
- Configuration development—Firm configuration update and file structural diagrams
- Configuration refinement—Engineering data sets, final system diagrams, and initial assembly tool design
- Product development—Designs updated to final loads, final production layouts
- Product definition—All data sets prepared for release, final inputs, and tool designs.

The first four stages focused on creating a complete integrated design before releasing the product definition requirements for fabrication and assembly. Detailed design was completed in Stage 5 to support final product definition release in Stage 6. The 777 program relied entirely on digital product definition, which included initiatives for digital pre-assembly, hardware variability control, and a process Boeing calls “design for reusability.”

The use of digital pre-assembly eliminated the need for physical mockups, which had traditionally been used to validate design integration and to define certain types of parts that could not be accurately described with two-dimensional drawings. Digital pre-assembly refers to the use of computer simulations to define parts and tools and to ensure that they will fit together before the parts data sets are released for production. Hardware variability control is a process that Boeing used to improve performance targets for shape, fit, appearance, service life, and safety.

These top-level characteristics are flowed down to the detailed part level and statistical analysis is conducted to optimize tolerance level and other specifications.

Boeing's "design for reusability" strategy refers to its effort to standardize certain parts and features of aircraft that could be used across different programs. A related aspect of this strategy was the identification of about 200 standard options that covered the majority of individual customer requirements. Provisions for these 200 standard options were incorporated into the basic design of the 777 to reduce change, error, and rework costs for individual customers.

The product definition changes described above resulted in significant cost savings for Boeing; in addition, quality control was improved significantly relative to previuos programs. These improvements in the product definition phase of the design cycle had their largest impact on costs and quality; the improvements do not appear to have significantly reduced design cycle times.

The 777 development program also included a wholly redesigned test program that focused on the validation of design requirements, certification regulations, and customer operations. The program included supplier component testing, Boeing standalone lab testing, and three other laboratories focused on system-level integration testing. These labs included the Systems Integration Laboratory, used to provide airplane-level validation, the flight controls tests rig used to test all flight control components, and a cockpit engineering simulator called CAB2. All of these labs relied heavily on computer simulation to reduce the need for physical testing.

The SIL performed almost 6,000 hours of testing for the 777 program. Almost 4,000 hours of testing were conducted before the first actual flight of the first test airplane. As the flight test program proceeded, changes in solutions were tested and validated in the SIL before their application on the test airplanes.

The flight controls test rig was used to test all flight control components. About 6,500 hours of testing was performed in this lab, which involved a significant increase in complexity relative to previous programs due to the fly-by-wire design of the 777.

As with the product definition phase, the innovative aspects of the 777's flight testing program related primarily to more efficient processes leading to cost savings. It does not appear that actual reductions in cycle time were generated; this is largely due to the significant increase in technical complexity associated with the 777 program.

Potential Benefits of Reduced Cycle Times and Likely Targets of Reduction Efforts

The benefits of CTR accrue at many levels and in a variety of forms, but the most important metric is at the firm level, and that metric is in profitability. CTR affects profitability in two related ways, savings in cost and savings in time.

- Savings in costs allow better pricing strategies. The same aircraft of a few years earlier can now be built at a lower cost. This allows for more profit per aircraft as well as additional sales due to a lower purchase price.
- Savings in time also translate into bottom line profits. Loan terms, including amount and interest rate will be lower due to a shortened time to break even and lower borrowing amount and quicker cash flow from the buyers.

All of these serve to create better shareholder value for the firm and a more competitive firm in the marketplace.

There are other ways to look at the benefits of CTR. One convenient way is to focus at the operational level of the firm. Here the benefits are driven by four major programs:

- Reducing engineering man-hours
- Reducing tooling hours
- Reducing test activity
- Implementing process and information technologies.

According to interviews with industry personnel, engineering man-hours are targeted for a 13 to 20 percent reduction over the next 5 years. The reduction program encompasses a wide range of projects, but almost all of them include some form of information technology. This is the modern form of substitution of capital for labor. A potential list of reduction programs follows:

- Automate design engineering, including incorporating knowledge-based tools into CAD
- Design analysis limited to 3-D solids
- Improve CAD skills of the workforce
- Develop propulsion aerolines rapidly
- Find solutions for blade containment

- Create a creation/design studio, as the auto manufacturers did
- Develop common structural analysis tools
- Apply CFD to the aerobody
- Analyze vehicle lines and loads analysis.

Tooling hours are targeted for 5 to 12 percent reduction over the next 5 years. These reduction programs involve incorporating industry best-tooling practices and quality control, as well of introduction of new simulation and manufacturing techniques. These reduction programs are shown below:

- Incorporate the best tooling practices for a flexible manufacturing center, including adjewel manufacturing
- Incorporate simulation of manufacturing processes
- Incorporate integrated tolerance analysis
- Create a single standard quality manual for all programs.

A set of test-related initiatives are expected to reduce test activity 8 to 12 percent over the next 5 years. These issues involve certification issues, redesign of testing activities, and development and deployment of new technology. These planned reduction programs include:

- Development of a 9 month flight test program (currently 12 to 36 months)
- FAA oversight given to aircraft manufacturer monitors – expanded delegation
- Standard test process with off the shelf test plans
- Validation capability
- Standard validation for propulsion system
- Application of smart sensors for testing
- Certification of avionics
- Propulsion certification and compliance.

The last area is the implementation of process and information technologies. These are the set of tools and practices not related to aircraft manufacturing in particular; but are associated with developing processes, practices, and tools that lead to a more efficient and productive operation of the firm at both the strategic and operational levels. Areas designated for emphasis include:

- Establish standard decision analysis tool set for the managers
- Implement portfolio management
- Screen IR&D projects in accordance with a set of objectives
- Overhaul data links to critical suppliers
- Develop generic airplane study capability
- Create a neural formation network
- Integrate into a paperless factory.

Chapter 4
Market Impacts and the Realization of Benefits of Reduced Cycle Time

NASA's program to improve its capabilities in vehicle development cycle analysis may benefit from new forthcoming economics evidence. A forthcoming study in the **American Economic Review** authored by C. Lanier Benkard provides new evidence on the nature of learning economies in the commercial aircraft industry which has direct implications for the benefits of reduced cycle time and for NASA's own vehicle analysis programs.

DYNAMIC EQUILIBRIUM IN THE COMMERCIAL AIRCRAFT MARKET

Benkard's paper[1] (available at: www.stanford.edu/~lanierb) suggests a significant departure from the usual characteristics of learning economies first described in papers immediately after World War II. During the war, it was found that the production of certain large-scale weapons systems (battleships, airplanes) exhibited significant reductions in costs over the production run as the workforce learned "how best to assemble and integrate complex systems into a single vehicle." These same types of learning economies are attributed to the production of modern commercial aircraft, which feature the integration of multiple complex systems. Because of the significant investment required to develop such vehicles, initial units may cost five to ten times as much as later units in the production run.

The existence of learning economies has significant implications for public policies,[2] briefly summarizing two of the more relevant implications:

- Because marginal costs are thought to decline continuously over the production run, some observers have deemed commercial aviation to be a "strategic" industry where government involvement through subsidy or other supports may result in the company gaining significant cost advantage over its competitors; in some instances these advantages may be long-term or "permanent."

- Traditional economic models of competitive markets do not accommodate declining marginal cost industries; pricing at marginal cost results in the firm not being able to recover its initial investment; such circumstances

[1] C. Lanier Benkard, "Dynamic Equilibrium in the Commercial Aircraft Market."

[2] See: GRA: "Economic Analysis of Aeronautical R&T: A Survey," (November, 1999), prepared for Office of Aerospace Technology, NASA Headquarters.

have been recognized in numerous regulated industries including transportation and communications. An essential issue for public policy is how best to set prices in such industries.

Recent Advances

While the learning economies' models provide useful information on some of the key characteristics of the commercial aircraft market, they do not accommodate some of the real world circumstances that have been observed. For example, for years economists have observed that under certain circumstances commercial aircraft manufacturers sometimes price their products below marginal cost. In almost any circumstance, such behavior would be deemed to be irrational since a company should not be selling a product for less than the resources consumed in producing it.

To explain these anomalies, Benkard developed a dynamic model for the commercial aircraft industry. For this discussion, the most important feature of this model is the observation that learning economies depreciate over time when they are unused. Benkard estimates that a firm's learning economies depreciate at an annual rate as high as 40 percent due to attrition in the workforce, changes in work assignments, and simple losses in proficiency in seldom repeated tasks. It is, therefore, important for the firm to maintain a constant rate of production, or to increase the rate of production in order to continue to benefit from decreasing costs promised by learning economies.

Benkard's paper is based on data on the L-1011 program. He observes that prices exhibit yearly variances of no more than 10 to 20 percent, but that average variable costs can vary by a factor as large as 50 percent. Using a sophisticated econometric model, he finds that the variance in annual production rates has direct and dramatic effect on learning economies. As a result, his model was able to explain why throughout much of its life, the price paid for L-1011 aircraft was below the company's average variable cost. When the firm was unable to maintain a steady production rate, its costs increased dramatically. This caused it to reduce its prices in an effort to fill empty production slots. It also explains why commercial aircraft manufacturers may choose to produce white tails in lieu of slowing down their production lines. The white tails may be a lower cost option than laying off workers and risking significant increases in production costs.

Dynamic Equilibrium Models

Benkard's model is dynamic in the sense that it portrays the features of the competitive process including the following:

- Outcomes in each time period (market shares, revenue, costs) for each competitor depend on the competition among them and the demand for products.

- Manufacturers compete by offering differentiated products and by varying price to optimize expected profits.
- Demand for aircraft may be affected by random shocks in the overall economy, which is consistent with other studies showing that the demand for aircraft is strongly correlated (with a lag) with overall economic conditions.
- In each time period, the manufacturer seeks to adjust its production rate and its price to maximize its expected profits over the remaining years of the product's life. The company's cash flow performance is directly affected by the product and price offerings of its competitors and the overall demand in the marketplace.

This kind of model captures the problems manufacturers have in maintaining a smooth production run over a product's life cycle to realize the maximum gains from learning economies. When demand fluctuates over the business cycle, the overall demand for aircraft rises and falls. Faced with changes in demand, competitors may choose to vary prices to smooth their production runs. During downturns in demand, prices may fall significantly below average variable costs, and stay there for significant periods of time as manufacturers make forward commitments to fill production slots. Alternatively, manufacturers may choose to vary the production rates. During downturns, they risk significant increases in production costs as output falls. This can have further consequences in the future if the manufacturers' production efficiency is low relative to its competitors.

In each time period, the model allows manufacturers to exit the market when the scrap value of an existing program is higher than the expected future cash flows. Likewise, new competitors may commit to enter the market in circumstances where new products (featuring new technologies) appear to have significant competitive advantage in the marketplace.

IMPLICATIONS FOR NASA VEHICLE DEVELOPMENT CYCLE ANALYSIS

NASA has already developed the detailed cost of modeling capabilities that are essential for evaluations of new vehicle developments. These models can also be used to assess the value of reduced development cycle times. Application of some or all of the dynamic features found in Benkard's model would improve NASA's capabilities by

- more accurately portraying the learning economies' issues faced by manufacturers and, in particular, the implications of varying production rates;

- the dynamic aspects of the aircraft manufacturing market including variations in the demand for aircraft and the effects of competing airplanes on expected manufacturer cash flows;
- portraying the advantages of reduced cycle time including, in particular, reducing the time between commitment to a program and its entry into the marketplace, and thereby improving the likelihood that expected production rates would be realized in the future.

Each of these potential improvements is discussed and illustrated briefly below.

THE EFFECTS OF VARIABLE PRODUCTION RATES ON LEARNING ECONOMIES

To illustrate how variable costs are affected by changes in production rates, we have developed a simpler version of Benkard's model. The following are the salient features of the model:

- Assume that a manufacturer is considering a new version of a large, single aisle aircraft with a target price of $55 million. The total market for this type of aircraft is estimated to be 100 units per year over the next 24 years.
- If the manufacturer can beat its competitor to the market with this version, it can command 70 percent of the market; once its competitor enters, its expected share will be 50 percent.
- Assume after the first year that the manufacturer can expect a 10 percent annual reduction in marginal costs in each year that production rates are at least 90 percent of the previous year's production.
- Assume in those years when production rates fall below 90 percent of the previous year's rate, learning economies will depreciate by four percent.
- Assume that the first 10 units have an average variable cost of $85 million per unit.
- Assume that the initial development costs spread over four years are $2 billion.

If the manufacturer can bring its product to market after 4 years of development, it will beat its competitor to market by 1 year and enjoy a 70 percent market share in that year.

A static analysis of the prospects for this project assuming a 7 percent discount rate is shown in Table 4-1. The expected net present value of the project is $622 million. The nominal internal rate of return is 8 percent, or 1 percent higher than the discount rate.

One of the features of Benkard's model is illustrated in Table 4-1. Notice that in Year 7, the marginal cost of production increases to $80 million per unit from $77 million the year before. The reason is that the number of units produced in Year 7 is lower than in the previous year resulting in the depreciation of the learning economies as discussed previously. However, in the static example, this is the only year where learning economies are depreciated because this is the only year where production rates vary. As a consequence after Year 7, learning economies continue unabated throughout the production run of the aircraft, so that by Year 24, marginal costs have fallen to $13 million per unit.

Effects of Varying Production Rates

To illustrate the implications of varying production rates on learning economies, we have adapted this model to make it dynamic in one dimension. We have assumed that the market for the subject aircraft has an expected or mean size of 100 units per year, with a standard deviation of 10 units. This means that approximately 90 percent of the time, the annual market will be between 80 and 120 units per year.

To determine the effects of this assumption on the expected net present value of the program, we simulated the aircraft program using the Crystal Ball program. After 500 iterations, we found that the expected mean net present value was ($2.1) billion with a median of ($1.9) billion. The results of the analysis are illustrated in Figure 4-1, which shows the expected net present values on the horizontal axis and their probabilities and frequencies on the vertical axes. The simulation of net present values has a standard deviation almost equal to the mean. This implies that the mean net present value is probably not a very robust estimate of the program's likely success or failure. The 90 percent confidence interval for program NPV is between ($5.0) billion and $0.7 billion.

The reason for the great variability in net present values is that production rates are no longer constant; as a result, variable costs rise or fall from year-to-year in a manner consistent with Benkard's findings that learning economies depreciate over time unless production rates either remain constant or grow. For example, in the static case, in the last year of production, marginal cost was $13 million per unit. The mean estimate in the dynamic model is $25 million per unit, with a standard deviation of $4.8 million. As a result, the last year's marginal costs varies in the range between $15 million and $42 million in the simulation, depending on how variable the realized sales are in the production runs simulated by the model.

This simulation has not captured all of the features of the Benkard's model.[3] For example, because of the wide variance in annual demand, a manufacturer might choose to lower its prices to fill empty production slots. This might be a more attractive alternative than experiencing the depreciation of its learning experience.

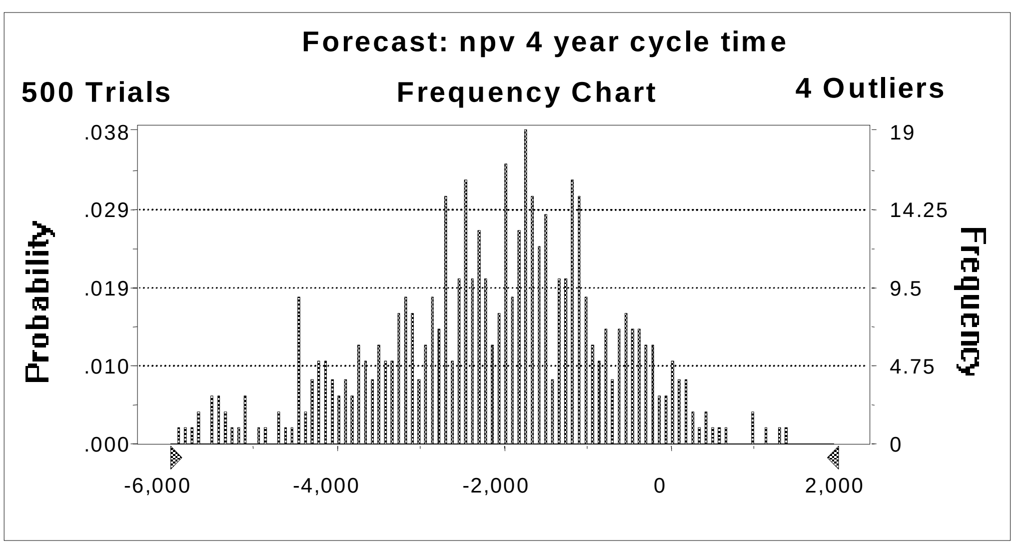
[3] Benkard's model utilizes a complex programming algorithm that is beyond the scope of this assignment.

Alternatively, it might be less expensive for the manufacturer to produce white tails than to layoff personnel and experience the learning diseconomies.

Table 4-1. Static Analysis of a Proposed Program

Year	Total Market	Incremental Units	Incremental MC	Cumulative Cost	Total Revenues	Total Costs	Profit	Discounted Profit @ 7%	Cumulative Discounted Profit @ 7%
1	100	0		500	0	500	-500	-467	-467
2	100	0		1,000	0	500	-500	-437	-904
3	100	0	85	1,500	0	500	-500	-408	-1,312
4	100	0	85	2,000	0	500	-500	-381	-1,694
5	100	10	85	2,850	550	850	-300	-214	-1,908
6	100	70	77	8,205	3,850	5,355	-1,505	-1,003	-2,910
7	100	50	**80**	12,183	2,750	3,978	-1,228	-765	-3,675
8	100	50	72	15,763	2,750	3,580	-830	-483	-4,158
9	100	50	64	18,985	2,750	3,222	-472	-257	-4,415
10	100	50	58	21,885	2,750	2,900	-150	-76	-4,491
11	100	50	52	24,495	2,750	2,610	140	67	-4,425
12	100	50	47	26,844	2,750	2,349	401	178	-4,247
13	100	50	42	28,958	2,750	2,114	636	264	-3,983
14	100	50	38	30,861	2,750	1,903	847	329	-3,654
15	100	50	34	32,573	2,750	1,712	1,038	376	-3,278
16	100	50	31	34,115	2,750	1,541	1,209	409	-2,869
17	100	50	28	35,502	2,750	1,387	1,363	431	-2,437
18	100	50	25	36,750	2,750	1,248	1,502	444	-1,993
19	100	50	22	37,873	2,750	1,124	1,626	450	-1,543
20	100	50	20	38,885	2,750	1,011	1,739	449	-1,094
21	100	50	18	39,795	2,750	910	1,840	444	-649
22	100	50	16	40,614	2,750	819	1,931	436	-214
23	100	50	15	41,351	2,750	737	2,013	425	211
24	100	50	13	42,014	2,750	663	2,087	411	**622**
					Nominal	IRR	**8.1%**		

Figure 4-1. Simulated Results of a Manufacture Program With Varying Annual Market Sizes

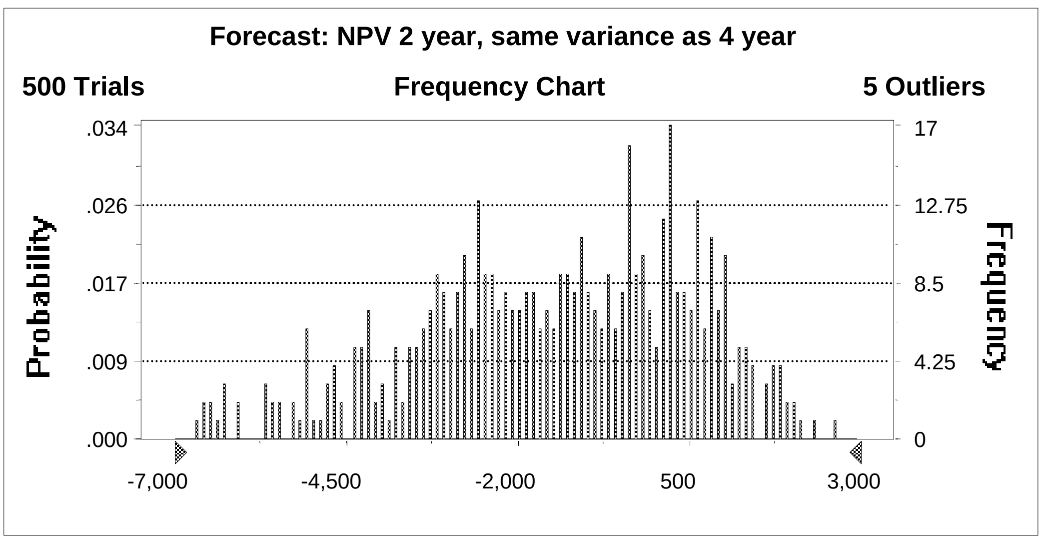


Effects of Reduced Cycle Time

Suppose that the same manufacturer had the opportunity to reduce its cycle time and get to market 2 years earlier than posited in the base case. Assume that the initial development investment was identical. As a result, the manufacturer would experience the full cost of the development program earlier, which, from a discounted cash flow perspective, is more expensive than spreading it over a 4 year period. Offsetting this, however, is the opportunity to get to market earlier, which would result in 2 additional years during which the company could expect to capture 70 percent of the market before its competitor entered.

A simulation run using these assumptions results in a slightly improved expected net present value of ($1.5) billion. The expected last year's marginal cost has also been reduced to $21.8 million per unit. The net present value results are illustrated in Figure 4-2.

Figure 4-2. Simulated Results of a Manufacturer Program With Reduced Development Cycle Time



The Effects of Reducing the Variance in Production Rates

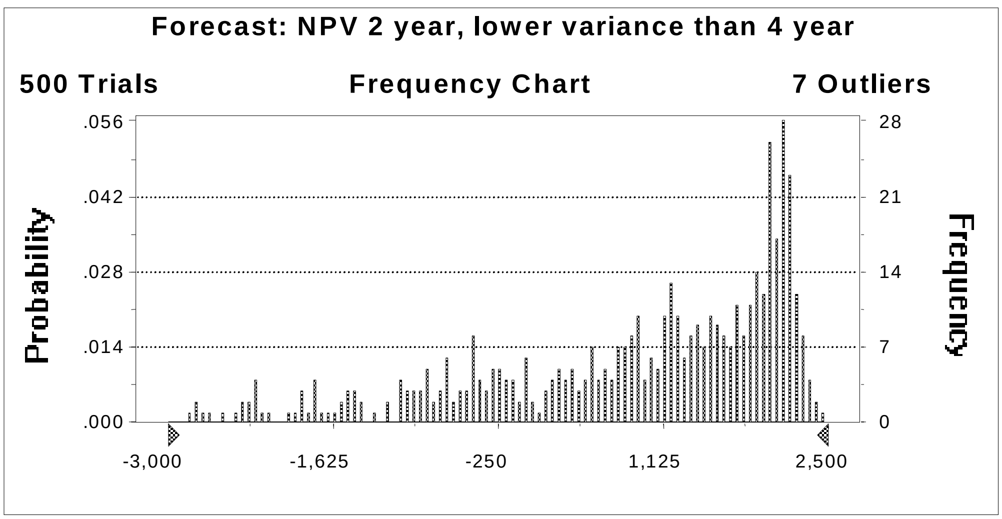
One potential consequence of getting to market earlier would be locking in more customers earlier than a competitor. This might give the company a better opportunity to smooth out its production run which would help it realize larger reductions in marginal costs over the product's lifecycle.

To simulate this set of circumstances, we have reduced the standard deviation, that applies to a market demand, from ten in the previous simulations to five in the present case. Assuming, again, that the company is now able to get to market in a two-year cycle time, the results are as follows:

- Expected or mean net present value is now positive $0.8 billion, a level that is higher than in the static case described earlier.
- The median present value is $1.2 billion, or approximately twice as high as the net present value in the static case.
- While the standard deviation of the simulation remains relatively high, the majority of the simulated net present values are positive.

The results for this simulation are illustrated in Figure 4-3.

Figure 4-3. Simulated Results of a Manufacturer Program With 2-Year Cycle Time and Reduced Demand Variables



As one would expect, the reduction in the variability in market demand has a dramatic effect on realized learning economies. The expected marginal cost in the last year of production for this simulation is $14 million per unit, with a median of $14.4 million. These last year marginal costs are 65 percent of the estimated level from the previous case where the company was able to develop an aircraft in only 2 years, but experienced greater variation in demand.

Of course, these results are only illustrative. But they suggest how powerful the insights are in the new learning economies' models.

IMPLICATIONS FOR NASA

The new economics literature on learning economies suggests that the risk inherent in new aircraft development may be even larger than originally posited. While commercial aircraft production is subject to significant learning economies, companies can benefit from these economies to a much greater extent if they are able to maintain or increase their annual production rates. When there are wide variations in production rates, there will be a significant depreciation in learning benefits, and the realized economics of the program may be disappointing.

As the simulations illustrate, just a few years of declining production can have a dramatic effect on realized learning economies. As firms are forced to layoff personnel and reorganize production activities, learning economies depreciate. Even when the production rates increase later during the life of the product, it may be difficult to overcome an earlier slump in sales. As a consequence, the last years of production when the marginal costs are expected to be extremely low may, in fact, be quite costly because learning economies have not been fully realized in the program.

These findings alone have important implications for the NASA program. To the extent that the risks in the commercial aircraft market have been previously underestimated in static models, there may be a more important role for the government (including NASA) to play. For example, to the extent that new R&T results make it possible to reduce aircraft development cycle time, the simulations have illustrated two benefits:

- Getting to market earlier means that the company will have more opportunities to dominate a particular market segment before a competitor can react; if a company can lock in more customers, it has a better chance of both producing more units and smoothing the production run over the product's lifecycle and thereby realize its learning economies.

- By getting to market faster, the forecast for the product and the expected profitability of the program are more likely to be realized; clearly a company will know more about a market a year from now than it will about the same market 5 years from now; the opportunity to reduce its market risk exposure is one of the chief benefits of reducing development cycle time.

Given the time and resources available in this project, we have not been able to develop a fully dynamic model. However, such a dynamic model would provide important insights on other issues relevant to the commercial aircraft market and to NASA programs. For example:

- Given the adverse consequences of interrupting production cycles, manufacturers may find it less expensive to produce white tails or significantly reduce their prices in order to fill empty production slots; by smoothing out the production run, learning benefits can continue to be realized and this may be preferable despite the costs of producing white tails or of reducing prices.

- Manufacturers' incentives to produce new products can be significantly influenced by first mover advantages; the opportunity to lock in customers and smooth out the production run can lead to substantial learning economies; once one company has successfully entered, the dynamic models suggest that its competitors may face a more difficult time justifying a new program (with similar characteristics); the second or third entrant into a product category may face greater variability in the demand for their products, and therefore are less likely to realize learning economies. As a result, one can expect that the products offered in the market will be differentiated; once one competitor is first in the market, others will wait until new technologies can be integrated into their product offerings and thereby provide a significant benefit to leap frog the initial mover.[4]

- The dynamic equilibrium models also tend to reinforce the application of strategic trade theory to the commercial aircraft industry; first mover advantages may be particularly important in this industry given the variability in the demand for aircraft over the product cycle; second or third movers in such markets are likely to be more severely disadvantaged than in other industries where production rates are larger and more predictable.

The new economics on learning economies is also generally supportive of the NASA R&T program. Greater risk in the commercial aircraft market portrayed in these dynamic models make it even less likely that private aeronautics firms will invest in optimal levels of research and technology. By stimulating the development and dissemination of new R&T, NASA's programs provide more opportunities for industry to develop more productive products more quickly. As a consequence, while first movers will always have advantages, these advantages will be eroded more quickly as new technologies are integrated into competing products. This will tend to happen more quickly through the stimulation of the R&T process.

[4] In turn, the first mover can use limit pricing to discourage new entry and/or can update its existing product with new technology.

Chapter 5

Benefits Framework for Cycle Time Reduction

The short-term benefits of CTR strategies primarily accrue to the aircraft manufacturers. Their benefits are fairly straightforward and are most easily denominated in the metric of dollars. On the other hand, the benefits to NASA are not as direct, nor are they easily calculated or denominated. NASA's benefits tend to be secondary and derived from the primary benefits that accrue to the aircraft manufacturers.

The previous chapter lists the potential benefits of reduced cycle times and likely reduction targets. To recap, at the operational level the reduction targets are to

- reduce engineering man-hours;
- reduce tooling hours;
- reduce test activity; and
- implement process and information technologies.

These reduction targets are not goals in of themselves, but are the operational links to a set of strategic goals. The strategic goals focus on reductions which affect the price that customers are invited to pay. They are reductions in:

- Product development cycle time
- Product cost
- Product/performance/change in sales
- Development program expense.

Product development cycle time refers to lowering the time of building any aircraft. In theory, it can be accomplished both with an increase or decrease in costs. The case of an increase in costs is not necessarily negative, but needs to be examined closely to see that the positive benefits of a shorter development time outweigh the negative benefits of a cost increase.

The preferred option is where costs either decrease or stay the same, but the time is shortened. The benefits in this form are multiplicative. Shorter cycle times lower borrowing costs while simultaneously increasing cash flow and lowering capital risk. Thus increasing the firm's competitive position while adding to shareholder value. Furthermore shorter times usually mean lesser production costs, and lesser production costs can mean increased sales because of a lower price. Shorter cycle times can also preserve sales and market shares in a fixed demand marketplace.

Product cost is a major determinant of the volume of aircraft sold, with the general rule being the lower the cost of the aircraft, the more that can be sold, and vice versa. Therefore product cost is a key component of the profitability of the product line. Lower product cost can be accomplished by either cost reduction and/or cycle time reduction.

Development program expense is very much related to Product cost. It represents the cost incurred until the first unit is sold. Those costs are key as they first determine the feasibility of the project then ultimately the profitability of the project.

These four strategic goals can also be examined as to when in the cycle time the savings occur. This is key because equal savings, either in money and/or time, at different times or phases of the development cycle can translate into very different final aircraft prices. Most of this effect is due to the nature of capital intensive manufacturing. Typical costs splits are 15/85, non-recurring/recurring. But, because the recurring manufacturing practices are defined by the non recurring portion of the cycle, a little savings in the non recurring costs can translate to major savings in the recurring costs. In addition, recurring costs are affected by a learning/improvement curve that determines the rate that costs decline with increased output. The decline rate is not a simple function of people learning to do tasks more efficiently, but is based more on correcting engineering and technical errors made in the non-recurring phase.

These four goals are also linked to each other, as changes in one will affect the others. This linkage is shown in Table 5.1. The table shows how a percentage change in one affects the other. For instance a 14 percent decline in Product development cycle time produces a 7 percent decline in Product cost.

Table 5-1. Linkage Of CTR Goals

	Product development cycle time	Product cost	Change in sales	Development program expense
Product development cycle time		-14/-7	-14/+10	-14/-7
Product cost			-7/+10	-7/-17
Change in sales				+10/-17
Development program expense				

This is a somewhat of aggregate look at the effects of CTR strategies. Another way is to look at where in the development cycle costs reduced. Given a simple cost profile over time as shown in Figure 5-1. The Cumulative cost profile is also shown there. Costs can be reduced in any of 3 ways:

Option 1: Costs are reduced by a constant amount over the entire cycle

Option 2: Costs (and hence time) are reduced late in the cycle

Option 3: Costs (and hence time) are reduced early in the cycle

These 3 results are shown graphically. Each of these costs reductions will produce a different cumulative cost profile.

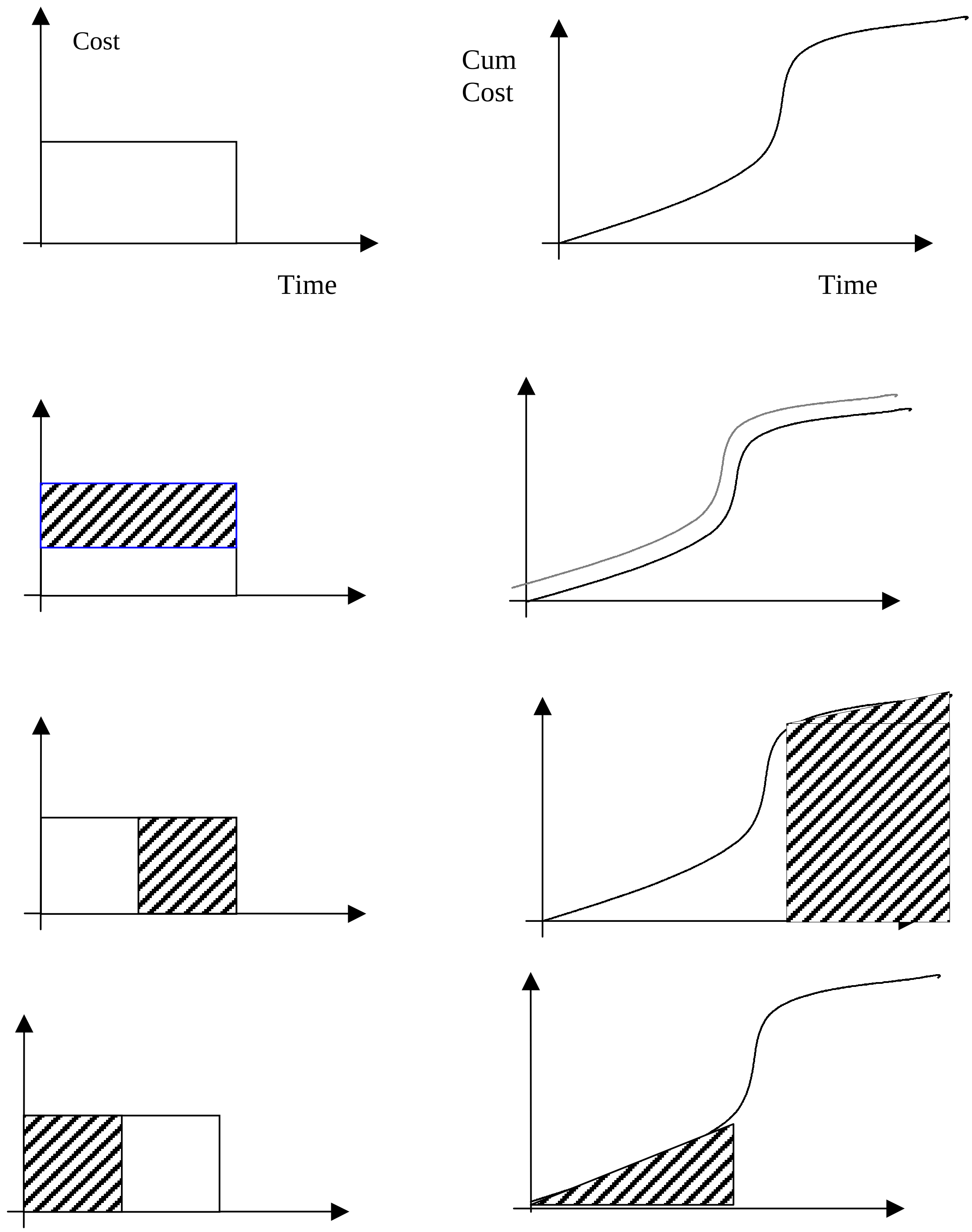
Option 1: Cumulative cost is reduced by a constant amount

Option 2: Cumulative cost is drastically reduced

Option 3: Cumulative costs have a minor reduction

This highlights the points that not only are reductions important, but where the reductions occur are even more significant.

Figure 5–1. Cost-Cycle Time Curve-Effects on Cumulative Costs



BENEFITS FRAMEWORK

Evaluation of the benefits that accrue to the aircraft manufactures is fairly straightforward. It is simply the net present value of the savings due to

- reductions in non recurring costs;
- improvements in the learning curve;
- initial cost of the first production unit; and
- increased buildup up the production rate.

This breakout in some sense may be the best as it is the factor components of the four strategic goals. There are other equally valid ways to characterize the benefits. They can also be calculated by cycle phase, by engineering group, or by any other reasonable classification

The benefits accruing to NASA are not as direct. Most are derived from the aircraft manufacturers benefits. Increased market share, sales and profitability translates into additional aircraft manufacturing and airline employment. Additional aircraft help lower relative emission and noise rates while raising safety rates. The technologies developed for civil aircraft cycle time reduction can first be applied to the defense aircraft industry and then adapted by other industries.

Chapter 6
Tailored Cost Model Analysis

During the course of this work effort, the study team was tasked to investigate the possibility of upgrading NASA's Tailored Cost Model (TCM) to facilitate the measurement of potential benefits likely to arise from the successful implementation of various NASA CTR related programs. TCM is an in-house computer model used by NASA that analyzes the economics of developing new commercial aircraft. This spreadsheet-based model relies on historical relationships between cost and various independent variables that characterize aircraft size, performance, features and complexity.

TCM uses weight as a primary factor in estimating the various cost components that are treated as part of the development process. Table 6-1 provides an overview of the major cost elements that form the basis for the model. A detailed description of the model is re-printed as Appendix B.

Table 6-1. TCM Cost Element Breakdown

COST ELEMENT	REMARKS
MATERIAL/EQUIPMENT	
• High Value Equipment	Engines/Avionics
• Manufacturing Material	All other material and equipment items
LABOR	
• Engineering	Design, Technical Staff, Liaison, Administration & Project Engineering
• Test Engineering	Flight/Ground Test Engineering
• Development	Test and Mockup Technicians
• ILS Engineering	Maintenance Engineering, Support Equipment Design, Training, Publications
• Manufacturing	Factory Labor (Touch Labor)
• Manufacturing Support	Industrial Engineering, Scheduling, & Factory Management
• Quality Assurance	Inspection & QA Management
• Tooling	Manufacturing Methods, Tool Design and Fabrication
• Project Management	Project & Business Management
OTHER DIRECT COSTS	Travel, Overtime Premium, Other

The primary purpose of the task undertaken here was to incorporate a true time dimension into the model so that changes in specific components of the development cycle could be entered and their impacts on the rest of the cycle analyzed. A further requirement was to keep the basic structure of the initial TCM intact; this was accomplished by appending information (in the form of additional worksheets) without modifying the original model.[1]

The add-ons to the model also were designed to:

- Be broadly consistent with the development cycle structure described above in Chapter 3.
- Facilitate the input of estimated time/cost savings from NASA program personnel who may not be familiar with the overall structure of TCM inputs and requirements.

DETAILED ANALYSIS OF TCM MODEL STRUCTURE

The general outline shown in Table 6-1 served as a starting point for the analysis; we then methodically went through each cost category to identify the ultimate input variables that depended directly on weight or that were fully hard-wired assumptions built into the model. This allowed us to identify the following six underlying cost categories:

- Basic Engineering
- Tooling and Facilities
- Ground Testing
- Flight Testing
- Manufacturing and Development Overhead
- Other Overhead Items.

Note that this basic structure does not include the "Early Configuration and Market Analysis" phase discussed in Chapter 3. By design, TCM was built to describe the design cycle process *after* Authority to Proceed (ATP) has been given for a specific project.

Within the TCM framework, the overhead items (5 and 6) depend on cost totals built up from the other categories and are usually entered as fixed percentages of these totals. In addition, Categories 1 and 2 each have their own overhead items, which depend on the category cost totals.

Using TCM nomenclature, the *Basic Engineering* category includes Design Engineering and the following overhead items:

[1] Note, however, that enhancements of the type discussed earlier in Chapter 4 related to learning economies and demand uncertainty were not addressed here.

- Technical Staff and System Engineering
- Management/Administration/Spec/Drafting
- Avionics Lab Operations (a function of avionics weight).

The *Tooling and Facilities* category includes Initial Tooling, Purchased Materials and the following overhead items:

- Manufacturing Support
- Quality Assurance.

Ground Testing is broken out into six specific testing subcategories:

- Wind Tunnel Tests
- Mockups and EDF
- Iron Bird Tests
- Static Tests
- Fatigue Tests
- Other Ground Tests.

Each ground testing category in turn includes Engineering, Development, and Purchased Materials components; in addition, the last four categories include a Manufacturing component.

Flight Testing is broken out into Engineering, Development, and Purchased Materials components.

For ease of exposition, *Manufacturing and Development Overhead* is treated as a separate cost category; in the TCM framework, it is strictly a function of the Manufacturing and Development cost totals estimated for each of the various *Ground Testing* components. It is broken into three subcategories:

- Manufacturing Support
- Quality Assurance
- Tooling M&R

Other Overhead Items is an amalgamation of the remaining cost items in the TCM. It is broken into five components, each with their own cost base:

- Integrated Logistic Support (ILS) — function of Design Engineering and Flight Test Engineering costs
- Project Management — function of Basic Engineering and in addition:
  - Initial Tooling
  - Tooling Overhead
  - Ground Test Engineering, Manufacturing, & Development
  - Flight Test Engineering and Development
  - Manufacturing Development and Overhead
  - Integrated Logistic Support
- Other Direct Costs — function of all items above
- Product Support — function of aircraft weight.

The structure outlined above is a complete and accurate representation of design cycle costs in the Tailored Cost Model that was presented to the study team. The total cost associated with each component in turn depends on two factors: total hours expended and unit labor cost (in dollars per hour). The only exceptions to this are Purchased Materials (which are entered into TCM as pure dollar amounts), Other Direct Costs (which is a function of all other TCM costs except Product Support), and Product Support (which is a function of aircraft weight).

DEVELOPMENT OF DESIGN CYCLE TIMELINE AND IMPLEMENTATION IN TCM

With the TCM cost structure in hand, the next task was to assign each cost category onto a timeline, and to make these assignments interdependent, so that changes when one component was begun or completed would affect all future components not yet undertaken. Additional discussions were held with industry personnel to ascertain reasonable assumptions regarding the interdependence and duration of the various design cycle components; these were combined with the information gathered in the manufacturer interviews to derive a “Base Case” timeline for a generic design cycle. Among other things, this required converting the TCM cashflow analysis from annual to monthly.

A brief summary of the Base Case timeline is described below:

Basic Engineering — To be consistent with the Phase I structure, Basic Engineering and each of its components was divided into two subcategories: Product Definition and Detail Design. For analysis, Product Definition was taken to represent 25 percent of Basic Engineering, with Detail Design representing the remaining 75 percent.[2] The beginning of Product Definition is Month 1, with a duration of 24 months. Detail Design begins immediately after Product Definition ends, with a duration of 18 months.

Tooling and Facilities — Begins when Product Definition is 75 percent complete and its duration of 36 months.

Ground Testing

- Wind Tunnel Testing begins when Product Definition is 50 percent complete; duration of 24 months
- Mockups and EDF begin when Detail Design begins; duration of 18 months
- Iron Bird Tests begin after Wind Tunnel Engineering ends; duration of 30 months
- Static Tests begin after Iron Bird Engineering ends; duration of 16 months
- Fatigue Tests begin when Static Test Development begins; duration of 24 months
- Other Ground Tests begins after Wind Tunnel Development ends; duration of 13 months.

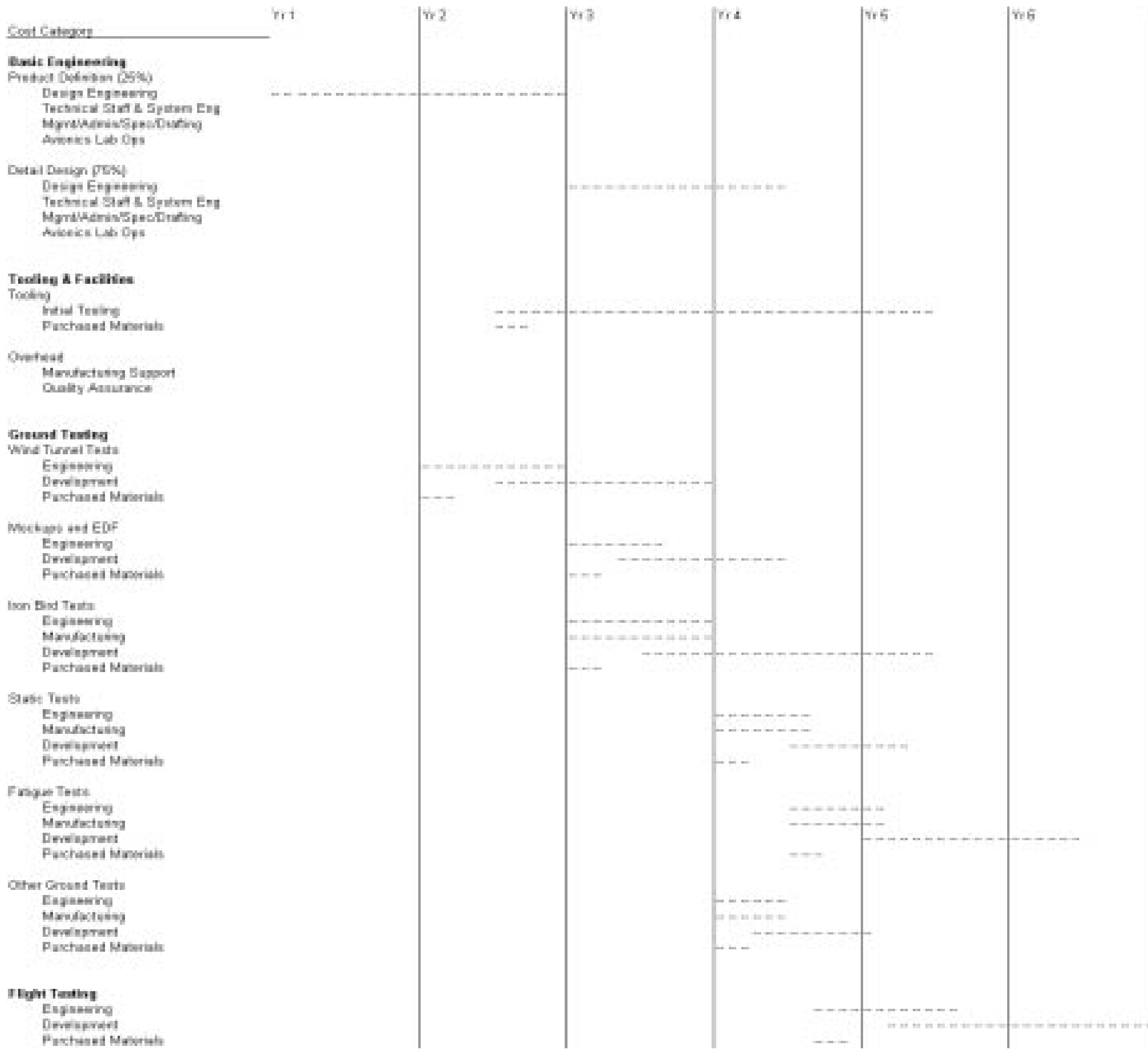
Flight Testing begins 9 months after Wind Tunnel Development ends; duration of 28 months.

The costs for Purchased Materials are assumed to be expensed over the first 3 months of each cost category. Finally, Manufacturing and Development Overhead and Other Overhead Items are expensed over time in direct proportion to the cost items on which they are based.

These assumptions result in a base case design cycle lasting 6 years; again, it is important to keep in mind that this does not include any design time allotted for early configuration and market analysis activities. A picture of the implied timeline is shown in Figure 6-1, which allows us to see the overlap in the various phases of the design cycle.

[2] This is consistent with the interview estimate that typical Detail Design costs are about three times as large as costs incurred as part of Product Definition.

Figure 6–1. Base Case Timeline



A detailed layout of the design cycle timeline is shown in Table 6-2; the table includes all of the cost elements described above, as well as unit cost assumptions from the TCM, start time descriptions and durations for each category, and hourly and total cost rollups. This table is taken directly from the "Dynamics" worksheet that has been added to the TCM spreadsheet file used to analyze a new 300-passenger aircraft. The columns labeled "Baseline" show the default assumptions described above. The layout enables the user to easily make changes to the Baseline time assumptions by changing either the formulas in the Start column and/or the number data in the Duration column.

A separate worksheet page entitled "Scenario" contains an input structure that allows the user to make changes in specific cost categories; these changes are entered as percentage changes from the baseline and can be used to assess projected time and cost savings from NASA or other programs that may impact on design cycle times. The layout is shown in Table 6-3. The category headings refer to the cost categories described above. In addition, the Basic Engineering section contains separate line items for various parts of the aircraft; these line items come directly from the TCM layout that makes up the Basic Engineering category.

Changes entered into the Scenario worksheet (Table 6-3) feed directly into the columns labeled "Scenario" in the Dynamics worksheet (Table 6-2). It is assumed that cost reductions translate directly into time reductions, so for example, a 25 percent reduction in tooling costs would be accompanied by a reduction in the time required to complete the tooling phase by 9 months (25 percent of the 36 months shown in the baseline). The revised cost data in turn feed into the "Cashflow" worksheet, where a monthly cashflow statement has been appended below the original TCM annual calculations. Here the user can view the impacts of the changes entered into the Scenario worksheet. The changes in net present value and/or IRR estimate may be of particular interest.

Table 6-2. TCM Dynamic Allocation By Month

Cost Category	Unit Cost	Start Description	Baseline Start	Baseline Duration	Baseline End	Baseline Hours	Baseline Total Cost	Scenario Start	Scenario Duration	Scenario End	Scenario Hours	Scenario Total Cost
Basic Engineering												
Product Definition (25%)												
Design Engineering	$105.40	Beginning	1	24	24	2,171,794	228,906,010	1	24	24	2,171,794	228,906,010
Technical Staff & System Eng	$105.40	Function of Design Engineering				2,151,303	226,747,376				2,151,303	226,747,376
Mgmt/Admin/Spec/Drafting	$105.40	Function of Design Engineering				381,676	40,228,684				381,676	40,228,697
Avionics Lab Ops	$105.40	Function of Avionics Wgt				9,225	972,290				9,225	972,290
Detail Design (75%)												
Design Engineering	$105.40	1 month after Product Definition ends	25	18	42	6,515,351	686,716,030	25	18	42	6,515,351	686,716,030
Technical Staff & System Eng	$105.40	Function of Design Engineering				6,453,910	680,242,128				6,453,910	680,242,128
Mgmt/Admin/Spec/Drafting	$105.40	Function of Design Engineering				1,145,029	120,686,061				1,145,029	120,686,090
Avionics Lab Ops	$105.40	Function of Avionics Wgt				27,674	2,916,860				27,674	2,916,869
Tooling & Facilities												
Tooling												
Initial Tooling	$64.48	3/4 thru Product Definition	19	36	54	14,715,165	948,833,808	19	36	54	14,715,165	948,833,808
Purchased Materials		First 3 months	19	3	21		77,705,078	19	3	21		77,705,079
Overhead												
Manufacturing Support	$64.48	Function of Initial Tooling				735,758	47,441,690				735,758	47,441,690
Quality Assurance	$66.96	Function of Initial Tooling				809,334	54,193,008				809,334	54,193,006
Ground Testing												
Wind Tunnel Tests												
Engineering	$101.68	Halfway thru Product Definition	13	12	24	126,703	12,883,181	13	12	24	126,703	12,883,161
Development	$59.52	Halfway thru Engineering	19	18	36	202,409	12,047,384	19	18	36	202,409	12,047,384
Purchased Materials		First 3 months	13	3	15		2,178,730	13	3	15		2,178,730
Mockups and EDP												
Engineering	$101.68	Same time as Detail Design	25	8	32	551,549	56,081,401	25	8	32	551,549	56,081,401
Development	$59.52	Halfway thru Engineering	29	14	42	146,936	8,745,750	29	14	42	146,936	8,745,750
Purchased Materials		First 3 months	25	3	27		760,404	25	3	27		760,404
Iron Bird Tests												
Engineering	$101.68	1 month after Wind Tunnel Engineering ends	25	12	36	179,634	18,264,177	25	12	36	179,634	18,264,177
Manufacturing	$59.52	Same as Engineering	25	12	36	82,234	4,894,568	25	12	36	82,234	4,894,568
Development	$59.52	Halfway thru Engineering	31	24	54	372,672	22,181,437	31	24	54	372,672	22,181,437
Purchased Materials		First 3 months	25	3	27		6,906,519	25	3	27		6,906,519
Static Tests												
Engineering	$101.68	1 month after Iron Bird Engineering ends	37	8	44	156,199	15,882,314	37	8	44	156,199	15,882,314
Manufacturing	$59.52	Same as Engineering	37	8	44	201,247	11,978,215	37	8	44	201,247	11,978,215
Development	$59.52	3/4 way thru Engineering	43	10	52	615,500	36,634,560	43	10	52	615,500	36,634,560
Purchased Materials		First 3 months	37	3	39		9,023,201	37	3	39		9,023,201
Fatigue Tests												
Engineering	$101.68	Same time as Static Development	43	8	50	265,576	27,003,766	43	8	50	265,576	27,003,766
Manufacturing	$59.52	Same as Engineering	43	8	50	1,073,317	63,883,916	43	8	50	1,073,317	63,883,916
Development	$59.52	3/4 way thru Engineering	49	18	66	429,976	25,592,172	49	18	66	429,976	25,592,172
Purchased Materials		First 3 months	43	3	45		17,417,375	43	3	45		17,417,375
Other Ground Tests												
Engineering	$101.68	1 month after Wind Tunnel Development ends	37	6	42	726,566	73,877,221	37	6	42	726,566	73,877,221
Manufacturing	$59.52	Same as Engineering	37	6	42	160,961	9,580,373	37	6	42	160,961	9,580,373
Development	$59.52	Halfway thru Engineering	40	10	49	2,365,122	140,772,081	40	10	49	2,365,122	140,772,081
Purchased Materials		First 3 months	37	3	39		52,676,617	37	3	39		52,676,617
Flight Testing												
Engineering	$101.68	9 months after Wind Tunnel Development ends	45	12	56	902,616	91,609,995	45	12	56	902,616	91,609,995
Development	$59.52	Halfway thru Engineering	51	22	72	955,969	56,899,275	51	22	72	955,969	56,899,275
Purchased Materials		First 3 months	45	3	47		2,735,226,869	45	3	47		2,735,226,866
Manufacturing and Development Overhead												
Manufacturing Support	$64.48	Function of Mfg/Dev				66,063	4,259,771				66,063	4,259,771
Quality Assurance	$66.96	Function of Mfg/Dev				746,517	49,986,772				746,517	49,986,772
Tooling M&R	$64.48	Function of Mfg/Dev				145,340	9,371,496				145,340	9,371,496
Other												
Integrated Logistic Support (ILS)	$96.72	Function of Design Eng + Flt Test Eng				714,047	69,062,626				714,047	69,062,626
Project Management	$111.60	Function of Basic Eng + Initial Tooling + Tooling Overhead + Grd Test Eng/Mfg/Dev + Flt Test Eng/Dev + Mfg/Dev Overhead + ILS				1,524,691	170,155,537				1,524,691	170,155,537
Other Direct Costs		Function of all items above					276,054,625					276,054,626
Product Support		Function of MEW					349,464,279					349,464,279
GRAND TOTAL						47,727,454	7,547,709,733				47,727,455	7,547,709,746
Production		1 month after Flight Testing ends	73	168	240			73	168	240		

Table 6-3. Scenario Changes

(Note: + indicates increase in cost; - indicates decrease)

	% Change from Baseline	Current Scenario Hrs		% Change from Baseline	Current Scenario Hrs
BASIC ENGINEERING					
Product Definition (25%)		**2,171,784**	**Detail Design (75%)**		**6,515,351**
STRUCTURES (COMPOSITE)			STRUCTURES (COMPOSITE)		
Wing Group	0.0%	0	Wing Group	0.0%	0
Fuselage Group	0.0%	0	Fuselage Group	0.0%	0
Tail Group	0.0%	0	Tail Group	0.0%	0
STRUCTURES (CONV)			STRUCTURES (CONV)		
Wing Group	0.0%	81,403	Wing Group	0.0%	244,208
Tail Group	0.0%	30,822	Tail Group	0.0%	92,465
Fuselage Group	0.0%	309,142	Fuselage Group	0.0%	927,425
Nacelle	0.0%	40,106	Nacelle	0.0%	120,318
Strut	0.0%	0	Strut	0.0%	0
Alighting Gear	0.0%	33,109	Alighting Gear	0.0%	99,327
PROPULSION GROUP			PROPULSION GROUP		
Turbofan Engine	0.0%	106,125	Turbofan Engine	0.0%	318,375
Accessories & Drive	0.0%	12,527	Accessories & Drive	0.0%	37,580
Start & Cntls	0.0%	0	Start & Cntls	0.0%	0
Thrust Reversers	0.0%	18,881	Thrust Reversers	0.0%	56,643
Fuel System	0.0%	16,272	Fuel System	0.0%	48,816
FIXED EQUIPMENT			FIXED EQUIPMENT		
DFCS/Flt Mgt System	0.0%	0	DFCS/Flt Mgt System	0.0%	0
Surface Controls	0.0%	157,634	Surface Controls	0.0%	472,903
Aux Power System	0.0%	16,849	Aux Power System	0.0%	50,546
Instruments	0.0%	7,998	Instruments	0.0%	23,993
Hydr/Pneu Group	0.0%	74,859	Hydr/Pneu Group	0.0%	224,577
Electrical Group	0.0%	25,356	Electrical Group	0.0%	76,068
Environ Cntl System	0.0%	52,330	Environ Cntl System	0.0%	156,991
Anti Ice System	0.0%	11,787	Anti Ice System	0.0%	35,360
Furn & Equipment	0.0%	636,147	Furn & Equipment	0.0%	1,908,442
Load & Handling	0.0%	0	Load & Handling	0.0%	0
Seats	0.0%	180,280	Seats	0.0%	540,841
Lavatories	0.0%	25,920	Lavatories	0.0%	77,759
Galleys	0.0%	93,920	Galleys	0.0%	281,761
LAMINAR FLOW SYSTEM			LAMINAR FLOW SYSTEM		
LFC Suction Surface	0.0%	0	LFC Suction Surface	0.0%	0
LFC Ducting	0.0%	0	LFC Ducting	0.0%	0
LFC Compressor/Gnrtrs	0.0%	0	LFC Compressor/Gnrtrs	0.0%	0
AVIONICS			AVIONICS		
DAC Avionic Equip	0.0%	33,868	DAC Avionic Equip	0.0%	101,603
BFE Avionic Equip	0.0%	73,954	BFE Avionic Equip	0.0%	221,861
Flt Provisions	0.0%	9,807	Flt Provisions	0.0%	29,421
Mission Provisions	0.0%	0	Mission Provisions	0.0%	0
SOFTWARE			SOFTWARE		
Operational Flt Software	0.0%	112,241	Operational Flt Software	0.0%	336,722
Ground & Eng Software	0.0%	10,449	Ground & Eng Software	0.0%	31,346

	% Change from Baseline	Current Scenario Hrs
TOOLING AND FACILITIES		**14,715,165**
Initial Tooling	0.0%	14,715,165
Purchased Materials	0.0%	
GROUND TESTING		
Wind Tunnel Tests		**329,112**
Engineering	0.0%	126,703
Development	0.0%	202,409
Purchased Materials	0.0%	
Mockups and EDF		**698,486**
Engineering	0.0%	551,548
Development	0.0%	146,938
Purchased Materials	0.0%	
Iron Bird Tests		**633,940**
Engineering	0.0%	179,034
Manufacturing	0.0%	82,234
Development	0.0%	372,672
Purchased Materials	0.0%	

USE OF REVISED TCM TO MEASURE DESIGN CYCLE BENEFITS OF NASA PROGRAMS

NASA provided a pre-filtered list of programs currently under development to the study team. The information provided included technology descriptions, estimated Technology Readiness Levels (TRLs) and likely implementation dates, along with subjective judgments about likely technical impacts and “minimum success” parameters. The task was to translate the program impacts into input variables that could be fed into the revised TCM model in order to assess the impacts on design cycle costs and time.

An initial list of 20 NASA programs were considered and reviewed for input into TCM. By agreement with NASA, an initial screening was done to drop those whose impact was focused on engine technologies. In addition, two additional programs were dropped because their impacts on the design cycle were considered to be minimal. For the remaining 11 technologies, 24 different analyses were carried out, involving four different-sized aircraft development programs (300 seats, 225 seats, 150 seats and 100 seats), three probability scenarios based on the range of likely impacts (Low, Most Likely and High), and two evaluation years (2007 and 2022).

The Low and High scenarios were based on the lower and upper limits of projected impacts, and the Most Likely scenario was estimated using the program's current TRL level and the following technical confidence mapping estimates shown in Table 6-4.

Table 6-4. TRL Impacts

Current TRL Level	Estimated Relative Impact (%)
1	35
2	55
3	70
4	80
5	85
6	89
7	91
8	93
9	95

For example, if a technology with a current TRL of 4 was projected to cut, say, flight test engineering time by between 10 and 20 percent, then the Low estimate would be set at 10 percent, the High estimate at 20 percent and the Most Likely estimate at 18 percent (= 80 percent of the gap between Low and High).

The evaluation years of 2007 and 2022 refer to a design program beginning in that year. By agreement with NASA, for the 2007 case only those technologies projected to be at TRL 9 by that year were included in the analysis; this accounted for a total of five programs. (All eleven programs were projected to be at TRL 9 by the year 2022.)

For each scenario, the goal was to estimate overall reductions in design cycle time and corresponding increases in manufacturer internal rates of return due to the programs' implementations. Table 6-5 lists all 20 programs and descriptions of their likely technical impacts and "minimum success" evaluations as provided by NASA; the table also indicates program inclusion or exclusion from the Year 2007 analyses.

Table 6-5. Overview of NASA Programs

PROGRAM	ELEMENT	SUBELEMENT	TECH NUM	TECH NAME	CURRENT TRL	YEAR OF TRL	TECH IMPACT	MISSION SUCCESS	APPLICATION	Include in 2007?	Include in 2020?
506	10	11	1	Computational algorithms for parallel processing	3	2009	100:1 reduction in combustor analysis time; 100:1 in compressor analysis time	Reduction in high fidelity analysis time will reduce engine development time by 25%	The simulations are being focused toward air breathing engine applications. However, the technologies are applicable to simulation tools used in space transportation, automotive, medicine, oil exploration, etc.	N	N
506	10	24	1	Highly parallel computing platforms	3	2009	Performance to cost ratio that is 10X better than the baseline systems on propulsion applications.	Performance to cost ratio that is 5X better than the baseline systems on propulsion applications.	The applications have focused on air breathing aircraft engines but can be transitioned to space transportation, automotive, medical, oil exploration, etc.	N	N
523	11	21	2	Noise Prediction and Analyses	3	2009	A system noise prediction tool accurate to within ±1EPNdB uncertainty for trajectory and/or configuration optimization. Take-off and landing operations need to be optimized to meet noise footprint constraints, driven by federal noise regulations and community acceptance standards.	A system noise prediction tool accurate to within ±3EPNdB uncertainty for trajectory and/or configuration optimization. Take-off and landing operations need to be optimized to meet noise footprint constraints, driven by federal noise regulations and community acceptance standards.	Civil and military aircraft. If we go to routine flight ops of number in 3rd generation launch vehicle vision of ..., there will be community noise impacts that this technology could impact as well. Additionally, applicable to aircraft acoustic detection (...) avoidance (...)	N	N
523	11	71	2	Coupled Multidisciplinary Simulation and Optimization	3	2008	Recent DoD studies predicted that together with a Flutter model elimination program (which this technology addresses partially) and a robust identification of critical flight loads study (which this technology addresses partially). Integrated aerodynamics, structures and flight controls in initial design synthesis could bring 50% reduction in engineering, manufacturing, development cost and 25% reduction in operations and support cost.	Integrated aerodynamics, structures and flight controls in initial design synthesis could bring 5% reduction in engineering, manufacturing, development cost and 10% reduction in operations and support cost.	Civil and military transports including supersonic flight. Launch vehicles	Y	Y
523	11	61	1	High Reynolds Number Skin Friction	3	2010	Current semi-empirical relations depicting dependence of skin friction on Reynolds number were developed with an uncertainty of 5% in the measurements. Goal of present program is to reduce this uncertainty to 2%. This reduction in the uncertainty of skin friction will translate to a reduction in predicted values of drag at flight Reynolds number of 2%.	Reduce the uncertainty of skin friction to 3%. This reduction in the uncertainty of skin friction will translate to a reduction in predicted values of drag at flight Reynolds number of 1%.	Civil and military transports.	N	N
523	11	61	2	Semi-span test techniques	3	2008	Reduction in design cycle time (1 month of wind tunnel testing; 3 months of flight testing). Provide improved model fidelity and reduced model costs.	Reduction in design cycle time (1 month of wind tunnel testing; 1 months of flight testing)	Civil and military transports	N	Y
523	11	61	3	Ground-to-Flight Performance Prediction	4	2003	WT Test Cycle Reduction: ~7 weeks or about ~50% of WT testing; Flight Test Cycle Reduction: ~4 weeks or about ~10% of flight testing; Cost: ~$4 million mainly through elimination of some WT models; Technologies: ~3% TARSC mainly through performance gains by understanding and using high Reynolds number effects (wing TE thickness, enable simplified high-lift system through	WT Test Cycle Reduction: ~7 weeks or about ~50% of WT testing; Flight Test Cycle Reduction: ~4 weeks or about ~10% of flight testing; Cost: ~$2 million; Technologies: ~1% TARSC	The knowledge gained here has broad application to all vehicle classes (GA, military, subsonic transports, access to space, high speed transport, ...) because we are addressing ground based testing effects, and the ability of CFD to predict the flight performance, loads, and S&C characteristics. Due to the nature of the testbed, some very specific benefits will be gained for subsonic transports in particular in both cruise and configuration performance.	Y	Y
523	22	31	1	Solution adaptive CFD grid generation	3	2007	-90% CFD grid generation time (engineering hours)		All vehicle classes. All speed regimes.	N	N
523	31	61	1	Subsonic High Lift Prediction	3	2006	-50% CAD-to-CFD analysis time; -50% in uncertainty for lift and drag predictions; -25% in WT and flight test time	-50% CAD-to-CFD analysis time; -50% in uncertainty; -10% in WT and flight test time	Targeted primarily at commercial transport but could conceivably be used on GA as well.	Y	Y
523	31	61	2	Airframe Noise Prediction	1	2010	-60% in prediction uncertainty; -25% wind tunnel and flight tests	-50% in prediction uncertainty; -15% WT and Flight tests	Primarily commercial transport but could apply to GA as well	N	Y
523	31	91	1	Computational Aeroelasticity	3	2008	-30% wind tunnel and flight test	-15% wind tunnel and flight test	Primarily commercial and military vehicles	N	Y
523	31	61	2	CFD for Stability and Control	3	2008	-50% wind tunnel test	-25% wind tunnel test	all vehicles	N	Y
523	31	61	3	High Fidelity MDO methods	3	2005	-90% time for design optimization in multiple disciplines	-50% time for design optimization in multiple disciplines	all vehicles	N	N
523	31	22	1	Engine component flow modeling	3	2009	-90% time in engine component flow modeling; -25% test time; -50% in uncertainty of performance predictions (from 12% to 10%)	-50% time in engine component flow modeling; -10% test time; -50% in uncertainty of performance predictions	commercial and military vehicles	N	N
538	10	0	1	Propulsion Economics	4	2005	For TP & subsonic transports: -40% turbomachinery design cycle time. Part effects varied w/ engine type (pre-noted)	-20% turbomachinery design cycle time; Part effects reduced by 30%	Commuter Turboprop and all subsonic transports (50 PAX through 300 PAX)	N	N
538	10	10	1	Eng. Design Cycle Improvements	4	2005	-30% turbomachinery design cycle time	-20% turbomachinery design cycle time	Subsonic engine development cycle	N	N
538	14	0	1	Airframe Methods	3	2010	AFM is to provide a 2% reduction in DOC+I and a 25% reduction in aerodynamic design cycle time for a new aircraft (baseline 2005/25 relative to the 1996 state of the art subsonic transport baseline.	1% reduction in DOC+I and 10% reduction in design cycle time	Technology will be applicable to aero design for any vehicle class. AST/AFM is tuning the techniques for large subsonic transports	N	Y
548	20	23	1	Icing Simulation - CFD Development	4	2006	a. Reduce the design cycle for ice prediction analysis by 30%; b. Extend the analysis tool usability for thermal and multi-element applications by 50%	a. Reduce the design cycle for ice prediction analysis by 15%; b. Extend the analysis tool usability for thermal and multi-element applications by 40%	The code will be useful to all classes of vehicles (both civilian and military, fixed and rotary wing), and both full aircraft and sub-system analysis.	Y	Y
548	21	23	1	Aircraft Icing Effects - Tailplane Icing Program Phase II	4	2005	a. Reduce the number of ice contaminated tailplane stall (ICTS) by 50%; b. Decrease development cycle time for tailplane design and testing by 40%	a. Reduce the number of ice contaminated tailplane stall (ICTS) by 50%; b. Decrease development cycle time for tailplane design and testing by 20%	Of particular benefit to the regional, corporate and general aviation aircraft manufacturers.	Y	Y
577	50	10	1	Systems Approach to Crashworthiness	3	2009	Reduce full-scale testing by 70%. Reduce human impact severity by 60% OR reduce occupant loads by 60%.	Reduce full-scale testing by 50%. Reduce human impact severity by 50% OR reduce occupant loads by 50%.	All aircraft classes	N	Y

The next step involved translating the likely program impacts described in Table 6-5 into TCM inputs. This necessarily involved some subjective judgments; further discussions with industry personnel were conducted to enhance the reliability of these judgments. The translation results are shown in Table 6-6. As seen there, many of the NASA programs considered here affected either the Wind Tunnel Testing and/or Flight Testing components of the development cycle. One open question recurring throughout the analysis was whether the impacts were likely to affect only the engineering portion of these test components, or the development portion as well. This is an important question since development costs are a large fraction of overall testing costs. For completeness, we computed results both including and excluding possible impacts on test development costs.

Table 6-6. TCM Inputs Affected By Various NASA Programs

PROGRAM	ELEMENT	SUBELEMENT	TECH NUM	TECH NAME	TCM Inputs Affected
522	11	71	2	Coupled Multidisciplinary Simulation and Optimization	Basic Engineering - Structures - Wing Group, Tail Group, Nacelle
522	11	81	2	Semi-span test techniques	Wind Tunnel Test, Flight Test
522	11	81	3	Ground-to-Flight Performance Prediction	Wind Tunnel Test, Flight Test
522	31	61	1	Subsonic High-Lift Prediction	Wind Tunnel Test, Flight Test
522	31	61	2	Airframe Noise Prediction	Wind Tunnel Test, Flight Test
522	31	81	1	Computational Aeroelasticity	Wind Tunnel Test, Flight Test
522	31	81	2	CFD for Stability and Control	Wind Tunnel Test
538	14	0	1	Airframe Methods	Wind Tunnel Test
548	20	23	1	Icing Simulation - CFD Development	Basic Engineering - Structures - Fixed Eqpt Design - Anti Ice System
548	21	23	1	Aircraft Icing Effects - Tailplane Icing Program Phase II	Basic Engineering - Structures - Tail Group
577	50	10	1	Systems Approach to Crashworthiness	Flight Test

For each analysis, total impacts on the design cycle will be a function of all of the (included) program's combined impacts. This brings into question how the programs overlap with each other. A detailed technical analysis of these overlaps was beyond the scope of this assignment. For present purposes, we have assumed that each individual program's impacts are independent, but are applied sequentially to the design cycle. So for example, if there were a total of three programs projected to impact flight testing, with savings of 10 percent, 20 percent and 20 percent respectively, then the combined impact of these programs would be to cut flight testing costs to 0.9*0.8*0.8 = 57.6 percent of the current baseline. Table 6-7 shows the estimated combined impacts by TCM category for all NASA programs taken together. Note that very large reductions in wind tunnel testing and flight testing costs are projected, particularly for the 2022 analyses.

These cost reductions were fed into the revised TCM spreadsheets for each of the four different aircraft sizes described above. The reductions feed through the time structure and into the cashflow analysis of the model. Summary results are shown in Table 6-7, where one can compare manufacturer internal rates of return (IRR) and total design cycle times under the Base Case and each of the scenarios.

Table 6-7. Estimated Combined Impacts on Design Cycle Costs of NASA Programs

	TCM cost category	Low 2007 (%)	Most likely 2007 (%)	High 2007 (%)	Low 202(%)	Most likely 200(%)	High 2022 (%)
Production Definition and Detail Design (Conventional)	Wing Group	5.0	7.8	10.0	5.0	7.8	10.0
	Tail Group	24.0	41.0	46.0	24.0	41.0	46.0
	Nacelle	5.0	7.8	10.0	5.0	7.8	10.0
	Anti-Ice System	15.0	31.0	35.0	15.0	31.0	35.0
Wind tunnel tests	Engineering (Dev.)	19.0	26.4	32.5	70.6	85.5	93.2
Flight tests	Engineering (Dev.)	19.0	26.4	32.5	46.9	61.2	71.1

Under the Year 2007 scenarios, the IRR's increase from around 8 percent to the 8.5—9.5 percent range, and overall design cycle times decrease by anywhere from 2 to 17 months from the baseline level of 72 months. Under the Year 2022 scenarios, much greater savings in wind tunnel and flight testing costs are assumed; this results in IRR's reaching over 12 percent and overall design cycle times decreasing by as much as 42 months. These results show the sensitivity of the model to assumptions about which NASA programs are likely to affect the design cycle and which cost components are affected, and suggest that further investigation into the combined effects of programs which all claim to impact a particular component (e.g., wind tunnel costs) may be warranted.

For present purposes, the incremental time impacts of individual programs can be estimated using a simple scaling procedure. The process was carried out only for the 300-passenger aircraft forecasts. First, individual cost reductions were fed into the TCM model one at a time for each NASA program, and the estimated impact on the overall length of the design cycle recorded. These impacts were then summed across all programs, and the total time reduction was compared to the results shown in Figure 6-2.

Figure 6–2. Summary Effects of NASA's CTR-Related Programs

Estimated IRR's and Development Cycle Times for 300-Passenger Aircraft
Baseline: IRR = 8.03%, Total Cycle Time = 72 Months, A/C Sold = 800 @$133.165 Million

		Low 2007	Most Likely 2007	High 2007	Low 2022	Most Likely 2022	High 2022
Excluding Wind Tunnel and	IRR	8.21%	8.24%	8.38%	8.55%	8.63%	8.75%
Flight Test Development	NPV at Baseline IRR ($mil)	84.885	98.655	166.457	244.468	285.468	335.779
	as % A/C Price	0.08%	0.09%	0.16%	0.23%	0.27%	0.32%
	Total Cycle Time	70	70	68	65	64	63
Including Wind Tunnel and	IRR	8.72%	9.06%	9.40%	10.49%	11.24%	11.87%
Flight Test Development	NPV at Baseline IRR ($mil)	321.483	468.978	613.162	1,035.347	1,291.709	1,484.701
	as % A/C Price	0.30%	0.44%	0.58%	0.97%	1.21%	1.39%
	Total Cycle Time	63	59	55	42	36	30

Estimated IRR's and Development Cycle Times for 225-Passenger Aircraft
Baseline: IRR = 8.07%, Total Cycle Time = 72 Months, A/C Sold = 800 @$88.500 Million

		Low 2007	Most Likely 2007	High 2007	Low 2022	Most Likely 2022	High 2022
Excluding Wind Tunnel and	IRR	8.26%	8.30%	8.45%	8.63%	8.74%	8.86%
Flight Test Development	NPV at Baseline IRR ($mil)	60.087	71.165	116.677	172.097	203.146	238.278
	as % A/C Price	0.08%	0.10%	0.16%	0.24%	0.29%	0.34%
	Total Cycle Time	70	70	68	65	64	63
Including Wind Tunnel and	IRR	8.79%	9.15%	9.51%	10.66%	11.46%	12.13%
Flight Test Development	NPV at Baseline IRR ($mil)	217.146	316.497	413.011	697.458	872.115	1,001.199
	as % A/C Price	0.31%	0.45%	0.58%	0.99%	1.23%	1.41%
	Total Cycle Time	63	59	55	42	36	30

Estimated IRR's and Development Cycle Times for 150-Passenger Aircraft
Baseline: IRR = 7.98%, Total Cycle Time = 72 Months, A/C Sold = 800 @$46.308 Million

		Low 2007	Most Likely 2007	High 2007	Low 2022	Most Likely 2022	High 2022
Excluding Wind Tunnel and	IRR	8.20%	8.24%	8.40%	8.62%	8.75%	8.89%
Flight Test Development	NPV at Baseline IRR ($mil)	39.973	48.383	76.298	114.737	137.015	160.614
	as % A/C Price	0.11%	0.13%	0.21%	0.31%	0.37%	0.43%
	Total Cycle Time	70	70	68	65	64	63
Including Wind Tunnel and	IRR	8.75%	9.13%	9.50%	10.72%	11.60%	12.36%
Flight Test Development	NPV at Baseline IRR ($mil)	135.485	196.699	255.813	431.186	541.475	625.960
	as % A/C Price	0.37%	0.53%	0.69%	1.16%	1.46%	1.69%
	Total Cycle Time	63	59	55	42	36	30

Estimated IRR's and Development Cycle Times for 100-Passenger Aircraft
Baseline: IRR = 7.96%, Total Cycle Time = 72 Months; A/C Sold = 800 @$38.170 Million

		Low 2007	Most Likely 2007	High 2007	Low 2022	Most Likely 2022	High 2022
Excluding Wind Tunnel and	IRR	8.19%	8.25%	8.41%	8.64%	8.79%	8.94%
Flight Test Development	NPV at Baseline IRR ($mil)	36.476	44.817	69.202	103.519	124.552	145.779
	as % A/C Price	0.12%	0.15%	0.23%	0.34%	0.41%	0.48%
	Total Cycle Time	70	70	68	65	64	63
Including Wind Tunnel and	IRR	8.76%	9.15%	9.54%	10.80%	11.72%	12.54%
Flight Test Development	NPV at Baseline IRR ($mil)	119.028	172.762	224.200	376.637	473.939	548.569
	as % A/C Price	0.39%	0.57%	0.73%	1.23%	1.55%	1.80%
	Total Cycle Time	63	59	55	42	36	30

As would be expected, the summed total of the individual impacts was greater than the grouped impacts shown in the table. The ratio of the grouped total to the individual summed total was then used as a scaling factor to reduce the estimated individual estimates so that their sum total would exactly equal the grouped total. These scaled results for individual NASA programs are shown in Figure 6-3.

Figure 6–3. Scaled Impacts on Cycle Time of Individual NASA Programs

(300-Passenger Aircraft)

PROGRAM	ELEMENT	SUBELEMENT	TECH NUM	TECH NAME	2007 - Most Likely Test Engineering Only	2007 - Most Likely Test Eng and Dev	2022 - Most Likely Test Engineering Only	2022 - Most Likely Test Eng and Dev
522	11	71	2	Coupled Multidisciplinary Simulation and Optimization	0.0	0.0	0.0	0.0
522	11	81	2	Semi-span test techniques			0.7	3.2
522	11	81	3	Ground-to-Flight Performance Prediction	0.0	4.0	0.0	2.5
522	31	61	1	Subsonic High-Lift Prediction	2.0	9.0	1.5	5.7
522	31	61	2	Airframe Noise Prediction			1.5	5.7
522	31	81	1	Computational Aeroelasticity			1.5	6.9
522	31	81	2	CFD for Stability and Control			1.5	6.3
538	14	0	1	Airframe Methods			1.5	5.7
548	20	23	1	Icing Simulation - CFD Development	0.0	0.0	0.0	0.0
548	21	23	1	Aircraft Icing Effects - Tailplane Icing Program Phase II	0.0	0.0	0.0	0.0
577	50	10	1	Systems Approach to Crashworthiness			0.0	0.0
				Sum of marginals	2	13	8	36

Chapter 7
Conclusions and Recommendations

This analysis was undertaken with the goal of examining commercial aircraft design cycle processes and identifying techniques and factors that may lead to future reductions in overall design cycle times. A complementary goal of the analysis was to examine how NASA's present research efforts may affect the design cycle.

The current NASA Airframe Development Cycle Time Reduction Goal is 50 percent by year 2022. The goal is not achievable based on the program analysis done by the LMI/GRA team. It may very well be the case that the program technology progress factors, as determined by the NASA experts were understated. If that is not the case, then the current roster of NASA Cycle Time Reduction programs need to be reexamined. Programs which duplicate the reductions of others should be replaced with other programs that offer non-duplicative reductions. In addition, new programs targeting a specific part of the cycle can be developed, as well as developing programs based on implementing best standards and practices.

Chapter 2 of the report provided a review of the literature and economic theory relevant for the aircraft manufacturing industry. In economic terms, the conventional view is that the industry has evolved into a duopoly, with Boeing competing against Airbus. This view must be modified somewhat, when considering certain segments of the industry; in particular, the growing demand for regional jet aircraft has led other smaller firms such as Bombardier, Embraer and Fairchild to enter the market and develop competitive products. Market demand and cost characteristics for the regional jet market are quite different than those for larger aircraft, and so the characteristics of the design cycle may also be different.

For this report, we have focused on design cycles that are relevant for larger (more than 100 seats) commercial aircraft. For this segment of the market, the duopoly characterization is appropriate. As discussed in Chapter 2, a number of economic factors affect the characteristics of the competitive environment in a duopoly; these include the nature of product differentiation, the rate of technological innovation, economies of scale, and government policies (including subsidies, loan guarantees, spinoffs from military research and development, etc.). All of these factors have had influences on entry and exit decisions in the industry, as do the high barriers to entry that characterize the industry. This in turn has impacts on the design cycle, as investments in cost (and time) saving innovations in a duopoly market will occur when the private benefits are expected to exceed the private costs. This occurs despite the fact that the resulting competitive advantage (and profits) may be competed away over time as the other firm "learns" or imitates the innovation for its own competitive purposes.

Chapter 3 of the report discussed the revised NASA design and development cycle analysis prepared in 1998. This analysis provided a useful starting point for modeling that broke down the design cycle into five sequential phases:

- Early configuration and market analysis,
- Product definition,
- Detailed structural, systems, and process design,
- Fabrication, assembly, and testing,
- Flight testing.

Interviews with two major aircraft design groups were held to confirm and refine the design cycle elements and times used in the base NASA model. These interviews essentially confirmed the validity of the basic NASA structure, although it was suggested that an additional phase involving tooling, facilities, and industrial equipment development could be added between Phases 3 and 4. A general theme common throughout the interviews was that the design cycle is entirely different for new products as opposed to derivative ones.

The interviewees also provided important guidance on likely areas of cycle time reduction efforts over the next several years. Four major target areas were identified:

- Reducing engineering man-hours,
- Reducing tooling hours,
- Reducing test activity, and
- Implementing process and information technologies.

A particularly important aspect of realizing the benefits of cycle time reductions relates to learning economies, which can have significant impacts on production costs and economic profits. Chapter 4 of this report discussed a simplified approach to examining learning economies in a dynamic framework. An essential feature of this analysis included an explicit assumption that learning economies depreciate over time when they are unused. This implies that it is important for a firm to maintain a constant or increasing rate of production over time in order to benefit from the decreased unit costs resulting from learning economies.

This has important implications for aircraft design cycles; the empirical simulations described in Chapter 4 showed that even small variations in production rates (especially in early years) can have dramatic effects on realized learning economies, and hence on net profits. This has important implications for reductions in design cycle times. In particular:

Getting to market earlier means that the company will have more opportunities to dominate a particular market segment before a competitor can react. If a company can lock in more customers, it has a better chance of both producing more units and smoothing the production run over the product's lifecycle and thereby realize its learning economies.

By getting to market faster, the forecast for the product and the expected profitability of the program are more likely to be realized. Clearly a company will know more about a market a year from now than it will about the same market 5 years from now; the opportunity to reduce its market risk exposure is one of the chief benefits of reducing design time.

Chapter 5 presents a framework for the analysis of CTR derived benefits. NASA's current Airframe Development Cycle Time Goal is a 50 percent reduction in cycle time. This Goal, if achievable today, would translate into

(a) a 25% decrease in Product Cost
(b) a 61% decrease in Development Program Expense
(c) a 36% increase in Sales dues to both increased demand from lower price and market share theft from early market entry.

For the airframe manufacturer the analysis is straightforward. CTR programs are designed to deliver aircraft faster and cheaper. The specific programs are designed to

(a) reduce engineering work-hours,
(b) reduce tooling hours,
(c) reduce test time, and
(d) introduce process control and information technology throughout the firm.

The purpose of these programs are to

a) reduce non-recurring costs,
b) reduce learning curve,
c) reduce first production unit cost, and
d) increase the production build-up rate.

At the operational level, the results of successful CTR strategies show up as

a) decreased production development time,
b) lower production costs,
c) increased sales, and
d) decreased in development program expense.

At the level of the firm these translate into increased cash flow, additional profits, and increased shareholder value.

For NASA and the general public, the benefits are those derived from the manufacturers successful implementation of a CTR program. At the primary level there are the set of technologies implemented by the manufacturers that can be modified and transferred other industries. In addition, there are the standard benefits derived from a healthy civil aerospace industry: additional aircraft sales, additional manufacturing and airline industry employment, and the subsequent economic ripple effects. The secondary effects include the introduction of new aircraft and replacement of old ones. These effects are less air and noise pollution as well as added safety in the commercial fleet.

In Chapter 6 attention was turned to NASA's Tailored Cost Model (TCM). TCM is an in-house computer model used by NASA that analyzes the economics of developing new commercial aircraft. This chapter described the new capabilities that were added to the model, including the incorporation of a dynamic time dimension and the addition of a simple input form to allow users to analyze the time and cash flow effects of changes in specific components of the design cycle.

Chapter 6 also presented estimated results from employing the revised TCM to measure design cycle benefits of various current NASA programs. Under the Year 2007 scenarios, manufacturer rates of return increase from around 8 percent to the 8.5-9.5 percent range, and overall design cycle times decrease by anywhere from 2 to 17 months from the baseline level of 72 months. Under the Year 2022 scenarios, much greater savings in wind tunnel and flight testing costs are assumed; this results in rates of return reaching over 12 percent and overall design cycle times decreasing by as much as 42 months.

Overall, the efforts undertaken in this project should provide a solid framework for further empirical analysis of aircraft design cycles. The results from Chapters 4, 5, and 6 in particular suggest that further efforts to improve the TCM or other empirical models of the design cycle should address important features such as the impact of learning economies, demand and production uncertainty, critical path analysis, and the combined interaction of different research programs whose effects may overlap with each other.

Appendix A
Design Cycle Goals for the NASA Systems Study

This questionnaire was provided to the two aircraft manufacturers design groups.

Note: Two primary data sources used to develop this questionnaire:

a) 1998 NASA Systems Study

b) Boeing deliverable to an AST contract

- Published reports of 777 development schedule
  - more relevant for new (as opposed to derivative) design cycles

RECONFIRM THE GENERIC DEVELOPMENT CYCLE

Generic Five-Step Process:

- Early Configuration and Market Analysis
- Product Definition
- Detail Design
- Fabrication, Assembly, and Testing
- Flight Testing

Is the above generic process a reasonable way to characterize aircraft development cycles?

Are you familiar with any other generic structures?

Are the differences because of age of the design or aircraft style and what are they?

How have the lengths and costs of each of the phases changed over time?

How and what are the changes in the phases you expect to see in the future?

What will be the desired effects? Are they likely to get them? And at what cost?

What processes need to be redesigned?

What processes can be eliminated?

Is the NASA Framework applicable to this firm or aircraft? Why or why not?

Early Configuration and Market Analysis — 12 Months (Only Loosely Discussed In NASA)

- Identify customer/product needs
- Manufacturer/customer interactions
- Design and tradeoff studies to identify range/payload parameters
- Market analysis — potential market size, likely customers, price ranges.

What else is going on in here besides manufacturer and customer iterations over range-payload designs?

Over time, how has this process been changing?

Where can improvements be made to shorten it? Say, decreasing response time between iterations? Multiple designs, contingent designs? Wider range of initial range-payload options? Seller or third party financing already in place?

What are the costs, benefits, and the effects on timely completion arising from these suggestions?

On average, or by specific aircraft, how much is spent in this phase?

How have customer/product needs been identified in the past? Specifics by aircraft type?

What is the nature of customer involvement in:

new versus derivative decisionmaking?

range/payload parameters (bottom line minimums or maximums) ?

engine choices (new versus derivative)?

What types of costs are involved?

Marketing staff

Engineering

Design studies

Paper/computer drawings

Other (e.g., engine analyses?)

Do costs vary by level of customer involvement or who the customers are?

Are formal design studies undertaken during this phase? How does this vary depending on new versus derivative?

If so, how many iterations are typical? How does this vary depending on new versus derivative?

How have advances in CAD/CAE affected initial design times and costs? Are additional important changes expected in the future?

Do unit costs of these studies decline as the number of iterations increases?

How is market analysis carried out? Projections of air travel demand, fleet sizes, other existing aircraft sales, market size for specific aircraft being considered? High/low ranges?

Are all likely potential customers contacted, or does analysis rest on a few large/important customers?

In general, is market development an ongoing process that could or should be separated from the rest of any specific design cycle?

Is launch decision always the breakpoint before going on to product definition?

Product Definition—24 Months

- Contains all preliminary design needed to develop a fixed mold line
- Three consecutive design/wind tunnel cycles, each 8 months:
  - Cycle #1 typically fails to meet performance or handling objectives
  - Cycle #2 meets performance objects, but typically fails handling objectives
  - Cycle #3 meets performance and handling objectives
- Re-evaluation and configuration update performed at end of each cycle
- Each cycle consists of four *parallel* wind tunnel models that go through design and testing:
  - High-speed aerodynamics (cruise)
  - Low-speed aerodynamics (takeoff/landing)

- ➢ Stability and control
- ➢ Loads.

How accurate is this general structure?

Does number of cycles ever go below or above three? Does it depend on new versus derivative?

How much play is there in the 8-month time for each design cycle? Are there reasons for going longer/shorter, or is it all re-evaluated in real time?

Are the four wind tunnel models basically independent? If no, what is the nature of the overlap?

Are there cost differences among the four?

Do all four have to be completed before starting another cycle?

Which among the four are most/least variable? Which have the greatest potential for time/cost reductions in the future?

How has the structure changed over time? Has it been shortened or lengthened?

Can any of these tasks be performed via computer rather than the physical test?

What new technology or information is needed to delete a test?

Can tests be performed concurrently?

Is there a finer level of detail or subphases to this stage? If so, what are they?

What are your suggestions as to how this phase can be shortened and improved?

Computers?

CAD/CAM?

Concurrent?

Faster iteration?

What are the costs, benefits, and the effects on timely completion arising from these suggestions?

Detail Design (18 Months)

- ◆ Contains all design needed to go from mold line to cutting metal

- Final loads determined within first 9 months
- Primary driver is creation of manufacturing drawings and their relationship with each other, which entails detailed structural analysis.

How are the design plans broken out? By aircraft system? Identify major systems, such as

- Fuselage,
- Wings,
- Landing gear/Tail/Rudder,
- Flight controls — internals vs. surfaces/attachments,
- Fuel system,
- Nacelle/Pylons,
- Electrical system and wiring,
- Cockpit,
- Cabin.

What is the nature of the costs associated with this design step?

What cost items can be broken out?

How much of the work (time/cost) is involved in integrating the systems to ensure design compatibilities?

Which systems take the longest to design? Does it vary by aircraft or by new versus derivative?

How are certification requirements incorporated into design?

What is the nature of simulations undertaken at this stage?

How are manufacturing processes and logistics incorporated at this stage?

Where is the greatest potential for time savings? For cost savings?

Fabrication, Testing, And Assembly (30 Months)

- Component fabrication
- Major assembly

- Static and fatigue testing
- Systems integration
- Software development
- Training and support services development
- End result is first unit of production that will enter flight testing.

Is this an accurate generic description of the subitems involved in this design step?

Where do each of these individual components appear on the time line? How does this depend on whether the program is new versus derivative?

To what extent are these activities concurrent with each other? (Fabrication/assembly is obviously not).

Where does the testing come in? Which items involve testing after fabrication? Which after assembly? How does this depend on whether program is new versus derivative?

Overall costs for this step? Cost estimates for each component?

Where is the greatest potential for time savings? For cost savings?

Is there a finer level of detail or subphases to this stage? If so, what are they?

What are your suggestions as to how this phase can be shortened and improved?

Computers?

Concurrent?

Faster iteration?

What are the costs, benefits, and the effects on timely completion arising from these suggestions?

What are the likely effects on the FAA Certification process?

Flight Testing (12 Months)

Required for certification

In general and by aircraft type, what is the time length spent in flight testing?

What is the cost? Total and by time outlay?

How has it changed over time? Has it been shortened or lengthened?

How has the computer cut costs and time? Will it continue to do so?

How much of this can be done by computer simulation?

How much of this is pilot ego?

Is there a finer level of detail or subphases to this stage? If so, what are they (are they checking out particular systems on a particular flights)?

What are your suggestions as to how this phase can be shortened and improved?

What are the costs, benefits, and the effects on timely completion arising from these suggestions?

What are the likely effects on the FAA Certification process?

Appendix B
Tailored Cost Model

The Tailored Cost Model (TCM) was developed by Greg Bell. A version of TCM was made available to NASA under contract with McDonnell Douglas Aerospace, led by Mr. Bell. Over a period of years, TCM was developed to provide a mechanism for creating independent cost estimates; these could be used to provide "should cost" targets for functional organizations, or to support conceptual design studies. This is a parametric model that relies on historical relationships between cost and one or more independent variables that characterize system size, performance, scope, or complexity. The cost elements shown in Table B-1, form the basis of estimate for the program acquisition phase of the life cycle cost.

Table B-1. TCM Cost Element Breakdown

Cost Element	Remarks
Material Equipment	
• High Value Equipment	Engines/Avionics
• Manufacturing Material	All other material and equipment items
LABOR	
• Engineering	Design, Technical Staff, Liaison, Administration & Project Engineering
• Test Engineering	Flight/Ground Test Engineering
• Development	Test and Mockup Technicians
• ILS Engineering	Maintenance Engineering, Support Equipment Design, Training, Publications
• Manufacturing	Factory Labor (Touch Labor)
• Manufacturing Support	Industrial Engineering, Scheduling, & Factory Management
• Quality Assurance	Inspection & QA Management
• Tooling	Manufacturing Methods, Tool Design and Fabrication
• Project Management	Project & Business Management
Other Direct Costs	Travel, Overtime Premium, Other

NON-RECURRING ENGINEERING

The aircraft system's nonrecurring engineering is modeled within three basic subgroups:

- Design Groups: These groups develop concepts, layouts, and detailed designs for structures, power plant, and various fixed equipment, avionic, and armament installations. Their efforts are modeled using weight dependent CERs. Software engineering is also modeled as a design group using lines of deliverable code as the CER driver.

- Technical Staff/Systems Engineering: These groups perform analyses that verify and validate the aircraft system designs and include aerodynamics, thermodynamics, loads, stress, flutter, vibration, guidance and control, and weights. System level design integration, engineering simulation, and reliability/maintainability engineering groups are also included. Conventional technical staff and systems engineering effort is modeled as a function of total design activity.

- Administrative/Management Engineering: These groups include drafting, configuration management, specification and process engineering, project engineering. The effort covers the management and control of the engineering design process and its documentation; it is modeled as a function of total design activity.

MOCKUP, TEST, AND DEVELOPMENT

The principal cost elements associated with test and mockup activity are test engineering and development labor. Test engineers are responsible for defining test requirements, designing test rigs and instrumentation, supervising the conduct of tests, data reduction, and the preparation of summary reports. The development shop builds test rigs and instrumentation, installs instrumentation into test articles supplied by the factory, sets up and performs the tests, and tears down the rig after test completion. The development shop is also responsible for building mockups. Class I mockups may be fabricated from wood and other inexpensive materials. Class II mockups may use actual aerospace hardware and may be used to define harness, tube, and ducting interfaces. Ground test, flight test, and mockup activities are modeled separately, with CERs for each engineering and development effort.

- Structural Tests: The aircraft structures are subjected to static and fatigue tests to validate ultimate strength and vulnerability to vibration and cyclic loading.

- Subsystem Qualification Tests: New/peculiar subsystem equipment will require qualification and miscellaneous ground testing (Shake/Bake/etc.).

Certain components may require environmental testing. Special functional rigs or bench testing (including an "iron bird" flight control rig) may be required.

- Wind Tunnel Tests: Wind tunnel tests place instrumented subscale models representing the aircraft into wind tunnels optimized for high speed or low speed aerodynamic evaluations. Wind tunnel test algorithms use tunnel occupancy hours as the independent variable.
- Software Integration Testing: A functional test bench is created to integrate software items and evaluate functional performance. Individual computer software configuration items are integrated to form the system. The system is tested to ensure that timing and memory constraints are satisfied, and that logic, interfaces, and protocols are correct.
- Flight Tests: Flight test activity is necessary to verify the performance of the integrated system. Flight test engineering covers the selection and design of instrumentation, data collection and analysis, and the presentation of findings. Development includes instrumentation fabrication and installation, servicing and maintenance of systems under test, and certain test activities such as ground vibration surveys. The flight test CERs use aircraft hours as an independent variable. The number of test flight hours for each element or subphase of the flight test program is estimated using historical development experience.

Non-Recurring Tooling and Factory Test Equipment

Tooling labor includes efforts to design and fabricate tooling hardware, development of numerical control programs, and creation of operation sheets and manufacturing methods.

The aircraft manufacturer's tooling consists of three principal kinds:

- Tooling associated with fabrication of primary and secondary airframe structures, such as wings, bodies, and empennage, etc.
- A family of tools needed to fabricate system provisions, such as tubing, electrical cables, and structural interfaces.
- A family of tools needed to integrate, assemble, and checkout the complete aircraft system. Included in this population are checkout and handling items designated as factory test equipment. These often resemble ground support equipment in form and complexity.

General purpose equipment such as Gerber cutting centers, milling machines, lathes, autoclaves, and DIT-MCO type systems are classified as capital equipment, and are not included here. TCM estimates a project's non-recurring tooling and factory test equipment by utilizing a series of weight dependent CERs.

BASIC FACTORY LABOR

Basic factory labor (also called touch labor) includes manufacturing efforts and processes required to fabricate, assemble, and install aircraft system elements. Also included are efforts to integrate and checkout supplier-furnished equipment. TCM uses a series of weight-dependent CERs to estimate factory man-hours for an idealized first unit (called T1). Factory effort to produce subsequent units is estimated by applying learning curves. Where large numbers of units are produced, the learning slopes tend to flatten for later production lots. The slopes are based on historical observations.

Learning Curve—is a measure of the improvement in productivity brought about by increased experience and skill levels. Historical data shows an improvement in direct workhours per pound of airplane against the cumulative number of planes produced for eight types of fighters produced by four manufacturers in World War II. When plotted in log-log form, a straight line results. This relationship can be depicted by the following equation.

$$E_N = KN^S \qquad \text{[Eq. B-1]}$$

Where:

> E_N is the effort per unit of production required to produce the *N*th unit.
>
> K is a constant, derived from the data at hand, that represents the amount of theoretical effort required to produce the first unit (TFU).
>
> *s* is the slope constant, which will always be negative because increasing experience and efficiency leads to reduced effort on a given task.

Every time cumulative production is doubled, the effort per unit required is a constant 2^S of what it had been. It is common to express the learning curve function of the gain for double the production. Thus, an 85 percent learning curve function means it requires only 85 percent as much effort to produce the (2*N*)th unit as it did to produce the *N*th unit.

If the percentage learning ratio is designated as L_p, the relationship between it and the slope is

$$-s = \frac{2 - \log L_p}{\log 2} \qquad \text{[Eq. B-2]}$$

For the total effort required for N units from 1 through N, the cumulative effort, T_n, is

$$T_{\mathrm{n}} = \sum_{1}^{N} E_{\mathrm{n}} \qquad \text{[Eq. B-3]}$$

The learning curve methodology in TCM relies on the use of the Wright curve approximation for this summation. Total hours for a given number of units is calculated using the following equation:

$$T_{\mathrm{n}} = \frac{T_1}{1+B}\left[(N+0.5)^{1+\mathrm{B}} - (0.5)^{1+\mathrm{B}}\right] \qquad \text{[Eq. B-4]}$$

Where:

T_n = Total manufacturing hours, N units

T_1 = Manufacturing hours, unit 1

B = (Log slope)/(Log 2)

This approximation improves as N increases.

Integrated Logistic Support (ILS) and Support Investment Non-Recurring

Integrated Logistic Support is a collection of efforts and products, including plans and analyses, hardware of various types, software and documentation, and services. The cost model develops ILS labor costs in three categories:

- Plans and Analyses: These occur during Full-Scale Development and include the following subtasks:
  - Maintainability Analysis
  - Reliability Analysis
  - Maintenance Planning
  - Repair Level Analysis
  - Identification of Ground Support Equipment items
  - Plans and Concepts for Provisioning, Publications, Training Systems, Site Activation, and Personnel Skill Requirements.

These engineering efforts are estimated as a function of the total nonrecurring engineering effort.

- Flight Test Support: This work element occurs during the FSD flight test activity, and includes field service maintenance and supply support activities. The labor is estimated as a function of total flight test engineering hours.
- ILS Commodities Nonrecurring: This activity includes formal design and development of ILS hardware and software as follows:
  - Organizational, Intermediate, and Depot GSE
  - Development of Training Curriculum and Design of Training
  - Equipment for Operation and Maintenance.
  - Preparation of Technical Publications, Provisioning Data, and other deliverable logistics data.

The estimate for serial production of GSE items, production of training equipment such as mobile trainers and simulators, and the production of initial spares is provided separately within a Support Investment cost summary. Small costs are also included for the maintenance and distribution of technical data. ILS commodity costs are estimated as a function of total aircraft production cost, based upon historical support investments for similar systems.

Support Labor And Program Management

The aircraft prime contractor/system integrator's support labor includes liaison and sustaining engineering, manufacturing support, quality assurance, and tooling maintenance and repair. Support labor efforts are developed by applying factors to factory, development, or tooling labor hours. Representative factors are shown in Table B-2.

Table B-2. Support Labor and Program Management Factors

Support labor element	f(Factory Mhrs)	f(Development Mhrs)	f(Tooling Mhrs)
Engineering liaison	.080	N/A	N/A
ILS sustaining	.020	N/A	N/A
Manufacturing support	.120	.010	.050
Quality assurance FSD	.150	.113	.055
Quality assurance production	.150	N/A	N/A
Tooling maintenance and repair	.120	.022	N/A

Program Management depends on the total number of prime contractor/system integrator in-plant labor hours. The cost model uses a program management factor of 4.5 percent for the RDT&E phase and 3.3 percent for the production phase. The size of the program determines the relative magnitude of program management effort required.

Material and Equipment Costs

Material costs include the raw materials, castings, forgings, and purchased parts required to fabricate and assemble aircraft systems and structures. Also included is a population of tubes, wires, connectors, shelves, and assorted items required to fabricate and assemble installations or provisions for the aircraft subsystems. Equipment items include propulsion systems, flight controls, avionics, electrical components, APUs, environmental systems, landing gear, instruments, furnishings, and numerous other purchased items.

- Supplier Non-recurring: Non-recurring costs are parametrically estimated using weight- or thrust-dependent CERs. The percentage of new design is used as a simple complexity adjustment for off-the-shelf or derivative cases. Supplier non-recurring costs are included in the full scale development program, and may also cover the cost of production line rate optimization.

- Theoretical First Unit (TFU) Costs: First unit raw material costs are parametrically estimated using weight dependent CERs. The CERs are derived from the cost of applicable raw materials per pound and historical usage factors (buy-to-fly ratios) associated with the manufacturing processes.

- Cost Curve Calculations: TFU costs are used for cost improvement curve analysis. Off-the-shelf items are cost-curved based upon the total number of units previously delivered. The cost curve methodology relies on the use of Wright curves. Total raw material cost for a given number of units is calculated using the following equation:

$$TRM_{\cos t} = \frac{TFU}{1+B}\left[(n+0.5)^{1+B} - (0.5)^{1+B}\right] \qquad \text{[Eq. B-5]}$$

Where:

TRM_{cost} = Total Raw Material Costs, n Units

TFU = Theoretical First Unit Material Cost

B = (Log Slope)/(Log 2)

The cost curve slopes used for these calculations are quite flat; initially 92 percent, quickly transitioning to 95 percent. The fundamental basis for such improvement is gradual reduction in rework, improvement in usage experience due to process review, and improved material price due to increasing purchase quantities as the production rate accelerates.

The summary of the TCM cost elements is shown in Table B-3. The corresponding labor rates are shown in Table B-4 and the inflation factors are shown in Table B-5.

Table B-3. Summary of TCM Cost Elements

COST ELEMENT	RDT & E							PRODUCTION			SUPPORT INVESTMENT				
	NR ENGR	TEST & DEV	TEST ART	NR TOOLS	FSD A/C	FSD ILS	PROG MGT	RATE TOOL	PROD A/C	PROG MGT	PGSE	TRAIN	SPARES	DATA	SITE ACT
MATERIAL/EQUIP.															
Manufacturing Materials		F	X	F	X	F		F	X						
Purchased Equipment			X		X	F			X						
LABOR															
Engineering	X		F		F				F						
Test Engineering		X							X						
Development		X									SUPPORT INVESTMENT COSTS ARE				
ILS Engineering						X			F		ESTIMATED AS FUNCTIONS OF				
Manufacturing			X		X				X		PRODUCTION FLAWAY COSTS				
Manufacturing Support		F	F	F	F			F	F						
Quality Assurance		F	F	F	F			F	F						
Tooling		F	F	X	F			X	F						
Program Management							X			X					
OTHER DIRECT COSTS	F	F	F	F	F	F	F	F	F	F					

X - Paranetrically generated estimate
F - Factor generated estimate

Table B-4. Hourly Labor Rates in 1989 dollars

Category	Rate
Project Management	90
Engineering	85
Test Engineering	82
Logistics	78
Quality Assurance	54
Manufacturing Support	52
Tooling/ Manufacturing Engineering	52
Development	48
Manufacturing	48

Table B-5. USAF Raw Inflation Index— Base Year1989

Fiscal year	Inflation factor
1985	0.811
1986	0.860
1987	0.907
1988	0.952
1989	1.000
1990	1.040
1991	1.085
1992	1.115
1993	1.145
1994	1.174
1995	1.207
1996	1.240

CASH FLOW FINANCIAL ANALYSIS

Cash Flow—Measures the flow of funds into or out of a project. Funds flowing in constitute positive cash flow; funds flowing out are negative cash flow. From an accounting point of view, cash flow is defined as:

Cash flow = net annual cash income + depreciation

One might consider cash income as "real dollars" and depreciation as a book-keeping adjustment to allow for capital expenditures. A simple example is shown in Table B-6.

Table B-6. Simple Cash Flow Sample

1. Revenue (over 1-yr. period)	$500,000
2. Operating costs	360,000
3. Gross earnings (1) - (2)	140,000
4. Annual depreciation charge	60,000
5. Taxable income (3) - (4)	80,000
6. Income tax (5) x 0.34	27,200
7. Net profit after taxes (5) - (6)	52,800
8. Net cash flow (after taxes)	
(7) + (4) = 52,800 + 60,000	$112,800

Discounted Cash Flow—An investment analysis that compares the present worth (value) of projected receipts and disbursements occurring at designated times in the future to estimate the return from the investment or project. Also called Discounted Cash Flow rate of return; Interest rate of return; Internal rate of return; Investor's method; or Profitability index. This method finds the rate of return that makes the present value of all receipts equal to the present value of all expenses.

When profitability is measured by the DCF rate of return, the inclusion of the inflation rate results in an effective rate of return based on constant-value money. To a first approximation, the DCF rate of return is reduced by an amount equivalent to the average inflation rate.

Rate of Return—Rate of return is widely accepted index of profitability. It is defined as the interest rate that causes the equivalent receipts of a money flow to be equal to the equivalent disbursements of that money flow.

In TCM a financial analysis for the project is performed, using the parametric cost estimate values as the basis for expenditures and a "floated" market price to determine revenues and derive a viable price for the desired aircraft manufacturer's internal rate of return. A graphical example is shown in Figure B-1. Figure B-2 shows the cash flow over time.

Figure B–1. Graphical Internal Rate of Return Example

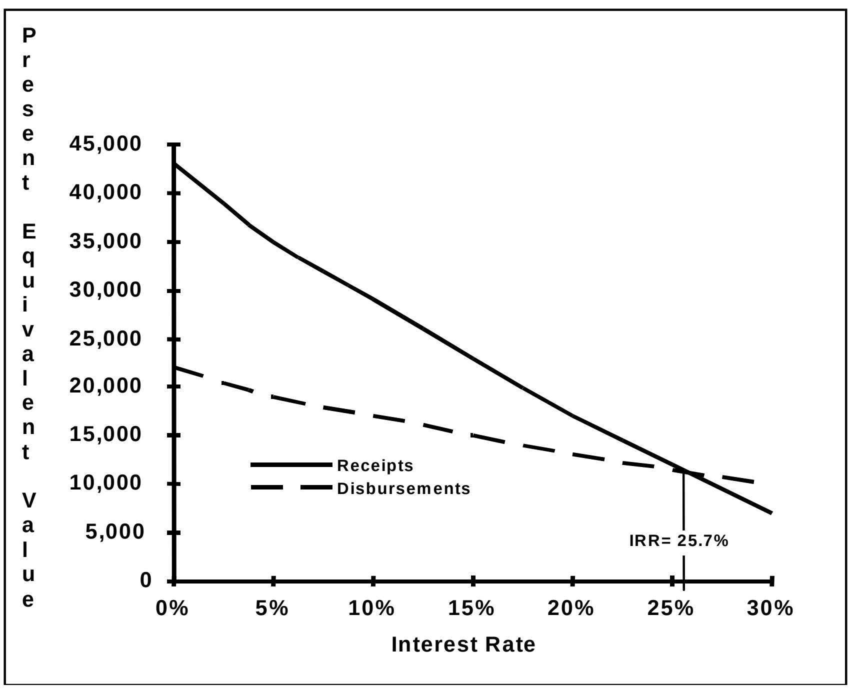
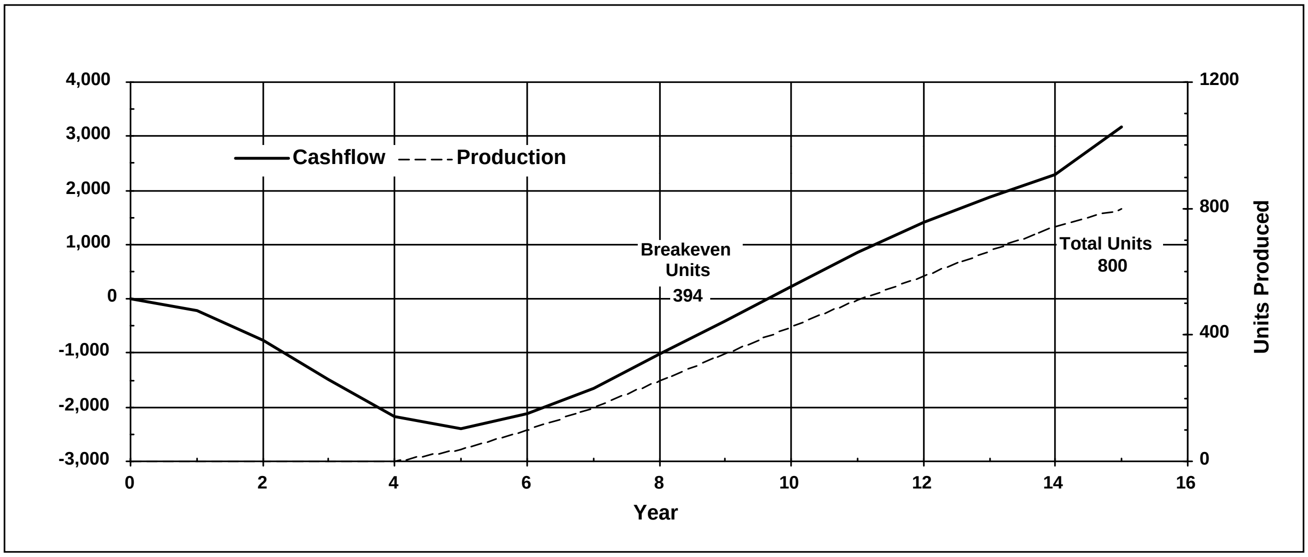


Figure B–2. Sample Cash Flow of an Aircraft Manufacturer



Present Value Method — In this method the object is to determine the future cash flows and discount these at an appropriate rate of return to obtain the net present value.

$$NPV = \sum_{i=1}^{n} \frac{(R_i - C_i) - t_c(R_i - C_i - D_i)}{(1+k)^i} + \frac{SV - t_g(SV - BV)}{(1+k)^n} - A - W + I \qquad \text{[Eq. B-6]}$$

Where:

NPV = net present value expected from purchase of the aircraft

A = purchase price of aircraft

W = additional working capital needed (spare parts, inventory)

I = Investment tax credit (if airline shows profits)

SV = salvage value of aircraft at the end of period *n*

BV = book value of aircraft at end of period *n*

t_g = tax rate applicable to the capital gains realized by the carrier

R_i = revenue realized from use of aircraft in period *i*

C_i = costs (operating, insurance, administrative, etc.) allocated to the aircraft in period *i*

D_i = amount of aircraft depreciated in period *i*

t_c = tax rate applicable to the carrier

n = length of period considered

k = appropriate discount rate (the after-tax cost of capital, a weighted average of cost of debit and cost of equity).

If the net present value determined from the equation is greater than zero, then the decision to purchase the aircraft is valid. By this technique, the expected cash flows (both + and -) through the life of the project are discounted to time zero at an interest rate representing the minimum acceptable return on capital. There will be some value of interest (*k*) for which the sum of the discounted cash flows equals zero; *NPV*=0. This value of *k* is called the discounted cash flow rate or return.

Appendix C
Economic Theory for the Civil Aircraft Marketplace

The number of sellers in the market is one of the factors that determine the market structure. Sellers (operating in the product or output market) can range from many to one, while buyers (operating in the resource or input market) also have the same range. The other two market structure determinants are product differentiation, or the degree to which the items sold vary by the seller and the barrier to entry, or the degree to which additional firms can enter the industry.

There are only four fundamental market structures as the three structural determinants are not independent: Pure competition, pure monopoly, monopolistic competition, and oligopoly. We will focus on the oligopoly market structure. It is characterized by few firms, with varying amount of product differentiation and varying degrees of difficulty of entry. By this definition, almost every industry is an oligopoly. Therefore we will refine the definitions to limit the analysis to industries similar to the airframe manufacturing industry. Therefore, the number of firms will range from 4 to 2; each firm will offer a differentiated product and the barrier to entry will be high.

The competitive practices in an oligopoly, including strategy, operations, and pricing, can be complex. One common practice is known as price leadership. Under this scenario, one or more of the firms announces a price, then the rest of the firms accept it. This can occur when one firm is more powerful than the other firms in the industry. This is also known as “dominant firm leadership with a competitive fringe.”

A firm (or firms) can become dominant for any or all of three major reasons: lower costs, superior products, or collusion.

Dominant firms can exist because they have lower costs. This lower cost can arise from a variety of sources including better management, better technology, better patents, more experience, more efficient operations, achievement of economy of scale effects, or operating higher on the learning curve.

Dominant firms can exist because they have superior products. This superiority can be real or it can be imagined. One firm can produce items of better quality, durability, longer lasting, easier operation, or any other relevant physical characteristic. Firms can also produce items that are perceived to be better. It can do so based on the psychology of reputation, goodwill, or advertising.

Dominant firms can exist because of collusion. This occurs when a group of firms agree to act collectively in any number of critical areas.

History shows that dominant firms do not stay dominant forever. Market share shrinks over time and moves the market from a dominant firm leadership oligopoly structure to some other one. This happens for a various of reasons. Dominant firms can get complacent, fail to offer customers the appropriate level of service, or customer demand can shift. On the other hand, the firms that make up the competitive fringe may bring new innovations and new products to the marketplace. The competitive fringe, in some sense, may try harder. In any case, history shows that dominant firms do not remain that way forever.

Over time, the market structure of dominant firm changes. What is of interest is when that structure changes to a duopoly, which is what has happened in the large airframe industry. There are three types of duopolies. They are Cartel, Cournot and Stackleberg. They are most easily distinguished by the prices they charge and hence, the profits they gain. The two firms in a cartel set prices and output such that industry revenue (and profit) is maximized. This is the equivalent of monopoly pricing: quantity is restricted and the highest possible price is charged. The Cournot Duopoly assumes that each firm considers the others choice of output as fixed. This results in both a higher quantity output and lower price than under the cartel solution. The Stackleberg Duopoly is characterized by a leader-follower relationship. The leader firm recognizes how the follower firm makes its quantity decisions and uses that information to maximize its profits. This results in a lower price and higher output than under the Cournot case.

The price-quantity structure is a function of a set of underlying market characteristics. To a large extent, certain types of characteristics determine the general market structure (monopoly, imperfect competition, and perfect competition) while others will determine the specific market structure (for example, which specific type of duopoly). Of key importance here are the types and levels of barriers to entry, economies of scale, investment strategies and the degree of product differentiation.

Barriers to entry are industry practices that determine the ease or difficulty new firms face as they enter the market, or as existing firms exit the market. Factors that translate into very high barriers (i.e., very few new firms are able to enter this type of market), include capital intensive industries having large advance sunk fixed costs, declining average costs, low volumes, high prices and using advanced technologies are of interest here.

The capital intensity deserves special mention. Firms must make large capital outlays, particularly unrecoverable outlays, in advance of both production decisions and expected profits. This binding commitment of resources affects both the level and flow of profits, and is sufficient to deter most firms from entering such a marketplace.

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13. ABSTRACT *(Maximum 200 words)*
Cycle Time Reduction (CTR) will be one of the major factors affecting the future of the civil aerospace industry. This focus is the end reflection of the level of competition in the commercial large carrier aircraft industry. Aircraft manufacturer must minimize costs and pass a portion of those savings onto buyers. CTR is one strategy used to move the manufacturing firm down the cost curve. The current NASA Airframe Development Cycle Time Reduction Goal is 50% by year 2022. This goal is not achievable based on the program analysis done by the LMI/GRA team. This may mean that the current roster of NASA CTR programs needs to be reexamined or that the program technology progress factors, as determined by the NASA experts, were understated. Programs that duplicate the reductions of others should be replaced with non-duplicative programs. In addition, new programs targeting a specific part of the cycle can be developed.

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