A System Dynamics Analysis of the Interaction Between the U.S. Government and the Defense Aerospace Industry

by

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Abstract

The defense aerospace industry is experiencing a dramatic decrease in product orders due to the downsizing of the U.S. military. Industry leaders have recognized a need to reduce both the cost and cycle time of defense aircraft design, development, and production while maintaining product performance, quality, and corporate profitability. As a result, several aerospace companies, the Department of Defense, and researchers at the Massachusetts Institute of Technology have formed a consortium—the Lean Aircraft Initiative (LAI). The LAI goal is to identify the path for implementation of "best" practices into the aerospace industry and the government departments with which they interact.

This thesis investigates the interaction of the government and the defense aerospace industry during the military procurement cycle. This interaction is demonstrated by analyzing the defense procurement system and the industry product development process using system dynamics principles. The resulting System Dynamics model identifies and seeks to quantify the interaction between the two organizations. The model interactions are calibrated against a recent military development project and the effects of variables on project performance and investigated through sensitivity analysis.

Thesis Supervisor: Stanley I. Weiss
Visiting Professor of Aeronautics and Astronautics

PREFACE

The upheaval of Soviet power has removed the principal perceived threat to the United States' national security. Responding to the changing structure of world power, the United States has begun re-evaluating the need for large military forces. Consequently, the Department of Defense budget has decreased annually as Congress has attempted to trim military expenditures by funding only the highest priority programs. This budgetary reallocation has drastically reduced both the number of defense aircraft programs under development as well as the number of defense aircraft purchased from each program.

As the sole funder of defense development programs, the Department of Defense wields great market influence. In a monopsonistic market, the customer has tremendous control of product specifications and effectively sets the price. While the sale of aircraft to foreign markets brings additional revenue to the company, as a rule these foreign governments do not directly initiate new aircraft *development*. With increasing competition for fewer development projects, many aerospace companies have gone out of business—either through bankruptcy or merger. As cost increase while funding and purchase quantities decrease, most companies have not been able to continue developing and manufacturing aerospace products in such low quantities. With no intervention, this trend could eliminate the U.S. defense aerospace industry and seriously cripple their efforts in the commercial aerospace industry as well.

The variability of the national security goals creates instability in the specified requirements for a military aircraft. Typically, an aircraft which actually passes the development approval milestone has already endured multiple changes. Even once a development contract has been awarded, the continuing evolution of contract requirements causes an increase in the workload to complete the project and wastes a certain portion of work already completed under the original design specifications. Considering that typical military projects incur a 5–7% per year real increase in expenses (to account for advancing technology), the more delays a project incurs, the higher the project's total cost.

While modern technology increases defense aircraft expenses, the complexity of modern aircraft accounts for only some of the longer cycle times. For example, each year a project is subject to funding changes due to the Congressional reallocation of funds. As most military development projects are run on a cost plus percentage profit contract, the company can only spend allocated funds. Therefore, when Congress cuts funding on a project—even minimally—the project will take longer to complete. In addition to design changes, funding changes also create extra work to re-baseline the project progress plan. This increases in costs which in turn increases the probability of further funding cuts and increases the project development time. Thus, the funding-change-additional-work-cycle is a major contributor to the high expense of modern military aircraft. For example, in 1955, 7 billion dollars (adjusted to 1982 dollars) purchased 1400 military aircraft. In 1982, that same 7 billion dollars purchased only 100 aircraft. While these 100 aircraft inarguably have greater capabilities, a certain number of aircraft are still necessary to complete a military mission. Norman Augustine, former Under Secretary of the Army, contends that if this trend continues, the U.S. will only be purchasing one aircraft per year by 2054.

The military-contractor product development process, the results of aircraft development under that process, and the potential benefits of process modifications are presented in this thesis.

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Michelle V. Bakkila

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To laugh is to risk appearing the fool.
To weep is to risk appearing sentimental.
To reach out for one another is to risk involvement.
To expose your feelings is to risk exposing your true self.
To play your ideas, your dreams, before the crowd is to risk their loss.
To love is to risk not being loved in return.
To live is to risk dying.
To hope is to risk despair.
To try is to risk failure.
But risk must be taken, because the greatest hazard in life is to risk nothing.
The person who risks nothing, does nothing, has nothing, is nothing.
He may avoid suffering and sorrow, but he simply cannot learn, feel, change, grow, love, live.
Chained by his certitudes, he is a slave; he has forfeited freedom.

Only a Person Who Risks is Free.

Anonymous

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CHAPTER 1

THE DEFENSE AEROSPACE INDUSTRY: PAST, PRESENT, AND FUTURE

To better appreciate the current defense aerospace industry, one should examine the early influences on the origin of the aircraft industry in the United States. After the Wright brothers' invention of the airplane in 1905, there was considerable public uncertainty regarding the utility of the "contraption." In fact, until 1915 the general public essentially regarded the airplane as a toy. With no substantive support or market, there was no incentive to establish an aircraft industry. However, the outbreak of World War I demonstrated to the United States and the Allies the actual strategic and tactical use of the airplane.

1.1 The Birth of the Military Aircraft Industry—World War I

During World War I, the Europeans explored using their aircraft for observation of the enemy's forces—troop size, movements, supply lines, etc. Aircraft reconnaissance was a valuable addition to the war effort. However, the Germans were the first to use the airplane as a strategic offensive weapon.

The German army commissioned the construction of thousands of planes to hurdle the stalemated front lines and penetrate into the heart of Allied territory. Many of these aircraft were used as bombers in an attempt to disrupt and destroy the munitions and supplies supporting the fighting troops. The remaining aircraft guarded these bombers from possible enemy attack (mostly ground based gunfire). The objectives of these air raids were

1. to interfere with the manufacture and procurement of supply and munitions,

2. to destroy locations of military value—docks, bridges, roadways, arsenals, factories, warehouses, and banks,
3. to force the maintenance of large forces away from the front to repel aerial invasion, and
4. to destroy the morale of the enemy's citizens.[1]

By 1915, American leaders had realized the United States' involvement in the war was inevitable. After acknowledging the offensive power of the airplane, Congress therefore requested the Army and the Navy to procure their own airplanes in preparation for entrance into the war.

The rapid increase in orders for aircraft, both from the United States and the Allies, caught the unstable and disorganized U.S. aircraft industry unprepared. Small, individual companies had been squabbling over patent infringements and, therefore, had invested little capital in production capabilities. Most aircraft patents were so vague that any company manufacturing and selling aircraft could be brought to court for patent infringement. Further, the relatively small market for aircraft simply did not justify high volume production systems.

When the War department encountered the state of disarray within the industry, officials asked the National Advisory Committee on Aeronautics to intervene. After more than a year of negotiation, an association of aircraft manufacturers was organized. Any aircraft company becoming a member of this organization had free use of all association aircraft patents. The government, as the purchaser of the aircraft, would pay the royalty fees which would be distributed among the association members.

Before the war, government procurement was a fixed price competitive bidding system. This system required each competing company to place a bid—the price at which it would sell the product to the government. The government then awarded the contract to the lowest bidder. The company was paid the bid regardless of any unexpected cost overruns. A fixed price system placed all of the risks of development on the prime contractor encouraged cost cutting procedures that allowed the contractor to increase profit by minimizing expenses.

In the name of efficiency, Congress added an option of cost plus contracting to the procurement system. Companies could receive payments equal to the cost of the product plus a percentage profit. The cost plus system removed the financial risks from the contractor and enabled more flexibility in experimental design but eliminated the incentive to bring the project in under cost because the company's profit was a percentage of the project cost.

With the legal obstacles resolved, the aircraft companies began construction of the planes ordered by the U.S. military and the allies. However, allegations of scandal arose quickly even in this early stage of the aircraft industry,. Accusations included claims that the newly formed aircraft association violated the anti-trust laws established in 1890. With the association controlling more than seventy-five percent of the industry price fixing was alleged, creating excessive profits at the expense of the government and the tax payer. In a country where free enterprise and competition were the cornerstones of business, such an accusation was a damaging blow to the struggling industry.

Formally requested to investigate, the Attorney General examined the possible improprieties of the organization of aircraft corporations. The resulting investigation caused a six week delay in the production of these crucial aircraft. Ironically, the Attorney General's findings indicated both that no anti-trust laws were being violated and that the profit margins of the corporations in the association were not only acceptable, but also less than those of comparable industries.

As the demand for aircraft continued to rise, companies sought loans to expand their operations. However, without a precedent by which they could establish premiums, insurance underwriters were reluctant to meet the companies' requirements. Combined with the general unwillingness of banks to trust the government to provide the funds to repay these loans, these hurdles made expansion of the companies' operations difficult. The association's chief spokesman, Mr. Samuel Stuart Bradley, bargained with the banks and insurance agencies by emphasizing the strength and size of the association as an indication of stability. Eventually, the association reached an agreement with the banks and underwriters to provide the funds for expansion and insurance for security. The delay in reaching this agreement created further delays for the companies as they strove to meet the government's orders.

As the companies grew, so did jealousy and mistrust. Attacks made against the association claimed the government was paying millions upon millions of dollars and receiving nothing in return. The opponents alleged the government was paying exorbitant royalties to the aircraft association for patent use. Suspicion from mismanagement to outright embezzlement of government funds abounded. Even after several separate investigations by disinterested third parties reported such allegations were misinformed at best and outright lies at worst, people were still unwilling to trust that the giant organizations were operating legally and ethically.

However, just as the industry was achieving a smooth, high capacity production rate, the war came to an end. The unexpected armistice caused the War Department to cancel the remainder of their orders—totaling over one hundred million dollars. The industry was left with useless equipment, tons of raw materials, and excessive capacity. With limited demand for aircraft, many of the companies went out of business and were liquidated for far less than their previous value.

The association of aircraft companies, used to the mutual trust and cooperation with which they had worked during the war, now faced a bleak future. They sought to promote commercial aviation, but with no regulatory structure to guarantee aircraft reliability, no air travel laws, and no landing facilities, there was little the companies could do to promote their product during times of peace.

The U.S. political leaders realized the key to modern warfare was the aircraft. The key to a strong air force during war time was a strong aircraft industry during peace time. This theory was published in a report from the American Aviation Mission:

> "Any future war will inevitably open with aerial activity far in advance of contact either upon land or sea, and victory cannot but incline to that belligerent able to first achieve and later maintain supremacy in the air. For economic reasons, no nation can hope in time of peace to maintain air forces adequate to its defensive needs except through the creation of a great reserve in personnel, material, and producing industry, through the encouragement of civil aeronautics. Commercial aviation and transportation must be made to carry the financial load [during peacetime to maintain industrial readiness in the event of war]."[2]

Therefore, the government sought ways to support commercial aviation; they asked the Post Office Department to transport mail by airplane. There were national campaigns to promote flying as a means of public transportation. Committees formed to generate air national policy, and regulations developed for traffic routes, inspection, safety, quality, landing sites, and a national weather service. The fundamental framework necessary for a commercial aviation industry was put into place.

1.2 The Depression

The rapidly growing public interest and support for the aviation industry increased the industry's "respectability". It became increasingly more likely that an aircraft company would be able to function in the post-war peace. However, the environment was far from stable. For financial and security reasons, many of the companies in the association began merging together until there were about seven major companies. Two of these large companies consisted of strong war time performers. Aircraft companies who preferred to remain autonomous found it more difficult to expand their companies—banks were unwilling to loan money to a company until it had received orders valued over $1 million. The smaller companies were forced out of business or into joining with the bigger firms.

The large companies contracting for the Army and Navy had relatively large profits during the depression. The smaller companies, limited by the specific nature of their product and the controlling forces of the larger companies, had little chance for survival. This issue was further aggravated by the fact that there was very little competitive bidding on government contracts. The Standard Statistics Bureau determined that only three percent of the aerospace companies between 1927 and 1933 (albeit the large ones) controlled around ninety percent of military business. The smaller companies had no opportunity to participate in the stable government business.[3] The larger companies, growing in experience and stabilizing their income from government contracts therefore controlled a large share of the developing commercial market as well. Economies of scale allowed the large companies to offer their commercial products at lower prices than their smaller competitors.

At this point, the government acquisition system was redesigned in an effort to address company proprietary designs. Contracts were broken into a design phase and a production phase. The design bidding process required companies to respond to military requirements in the form of a proposed design and indicate an expected cost. Another bid would be required when the Army or Navy circulated the winning design for manufacturing rights.

The industry responded violently to this new system. It claimed, and justly so, that the design company was not compensated for the excessive money invested in personnel, training, and experience to generate the design. The military refused to pay royalties on the design, therefore the companies felt they had a right to recoup these costs by being granted the manufacturing contract. They believed that in the competition to win the design contract, a fixed cost contract, the companies would underbid themselves (due to the uncertain nature of experimental design). Furthermore, they claimed that splitting the design and the manufacture would introduce inefficiencies as a another company would have to try to understand a design they had not developed before they could build it.

Congress eliminated the cost plus contract option at the end of the war so the only remaining option was a fixed price contract. Military procurement officers, used to working closely with their industry counterparts, agreed with the corporate concerns raised regarding the two step bidding system. Since there was no requirement that a contract must be let on a competitive basis, contracts were negotiated and the competitive bidding process was all but ignored. Allegedly, nearly all contracts in this period were let on a non-competitive basis, negotiated between the military procurement officer and the company of his choosing.[4] However, partiality or favoritism did not appear to cause unfairness in the contract award. Due to corporate realignment and mergers, there were less than seven companies that were *capable* of manufacturing the aircraft in question. Of these, two were conglomerates of several smaller companies. Government and commercial business was fairly evenly distributed between the two conglomerates, accounting for six of the corporations, as shown in Figure 1.1.

It was at this point that the first requirements for audits were included in the procurement process by Congress. In an attempt to maintain the dependence of the Army and the Navy on Congress, competitive bidding was reasserted as the prime method for contracting. The limitations on utilizing negotiation to let a contract were increased and to assure that contracting officers used competitive bidding, the Secretary of War and of the Navy were required to perform audits and report annually to Congress on their findings.[5]

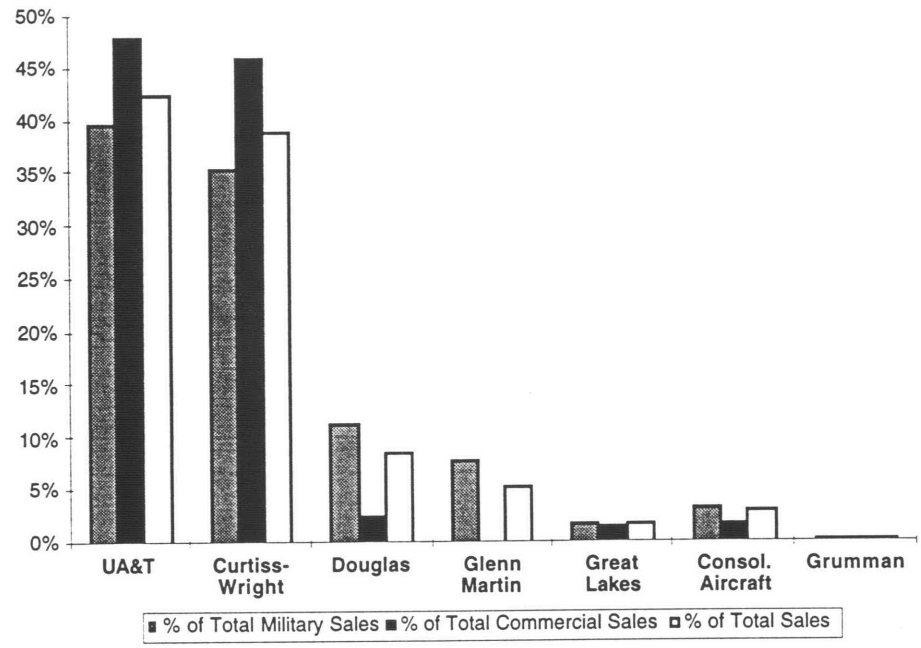

Figure 1.1 **Distribution of Business Between Companies in 1927-1933.**[6] UA&T consisted of Boeing, Chance Vought, and Pratt & Whitney. Curtiss-Wright consisted of Curtiss, Wright, and Keystone. The remaining were independent companies.

The Air Corps Act, which included the auditing described earlier, was self-contradictory. While in one section it granted the authority to the procurement officer to award contracts to the lowest bidder, in another section it indicated that the selection could be made based on contractor reputation and product quality. Even at this early stage in "procurement regulation life", laws were confusing, contradictory, and included too many explicit clauses regarding the Secretary's discretion. Overall, the act made procurement laws exceedingly difficult to interpret.[7]

Even though the aerospace industry was in profound public, legislative, and judicial disfavor in 1934, this image had completely changed by 1938. At this point it was clear that Germany, Italy, and Japan were on an aggressive campaign against their neighbors. Japan took advantage of a minor clash with Chinese troops in 1932 to move in and conquer Manchuria. Hitler removed Germany from the League of Nations in 1933, began a massive build up of the German troops, and by 1936, Germany had invaded Rhineland. Mussolini sent Italian troops to Ethiopia in 1935 and had captured it by 1936.

It was the cooperation between Germany and Italy in the Spanish Civil War that stabilized their association and gave them a stronger position in Europe. With the renewal of Japanese aggressions and Hitler's strong invasions in 1938, the United States and the other Allied powers realized that their earlier efforts to curtail aggressive expansion had been too late in implementation and largely ineffectual.

The aviation industry now operated in a "defense at all costs"[8] environment. However, even in such a strong environment, many of the issues of the earlier industry were not forgotten. With disclosure of the excessive profits made on government orders, several laws were enacted designed to control such profits. Congress required that ten percent of military aircraft and engines be constructed in military plants, supposedly to allow the government a standard by which costs could be measured.

The government also passed legislation that profit on Navy orders be limited to ten percent. Army orders were regulated to twelve percent profit years later. However, the same legislation allowed profit to be averaged over a period of years when calculating the limit, thereby allowing for increased actual profits in wartime years.

Congressional officials finally agreed that neither the bidding nor the negotiation process awarded the government with both high quality and low cost, so other procurement options were explored. Bidding for a production contract required a prototype to be built and presented to the Army. Decisions could then be made on both cost (as reported in the contract) and on quality (as seen by the prototype). A handbook of standards for military contractors was assembled as a guide for the military procurement processes. However, these procedures discriminated against smaller companies without the engineering staff to effectively compete for the design, and without the experience or funds to build a prototype. It was a viscous cycle. Without a contract, smaller companies could not generate the revenue necessary to expand their operations and build their research base. Without operational proficiency and engineering strength, they didn't stand a chance of winning a contract.

During this time that the first aerospace union was formed. President Franklin Delano Roosevelt had instituted several acts involved with his New Deal. The National Industrial Recovery Act established rules for fair competition in business, and stated that "workers had the right to bargain collectively with employers through representatives of their own choosing .

. ."[9] These codes of business conduct had not been implemented in the aerospace industry. For many years, the U.S. judiciary debated the legality of such acts. In the interim, the average aerospace company did not recognize the unions as legal entities and therefore ignored their demands. Although the subsequent strikes in the aerospace industry were unsuccessful (the strikers demands were not met), shortly after the incidents, the United Aerospace Workers union was recognized by the company management, under federal mandate.

1.3 World War II: Wartime Performance

Even though the United States had not entered World War II, increasing aggressions throughout the world caused changes in the United States' political policy as early as 1934. Congress took steps to limit the sales of munitions internationally. Since there was little distinction between a military aircraft and a commercial one, most aircraft were strictly limited to sale within the United States and to countries who were not at war. As the war fever began to spread in Europe, aircraft companies were also limited in selling certain aircraft *components* abroad. This act attempted to keep the U.S. disengaged from the rising European and Asian conflicts. However, the law clearly stated that war was a *declared* state of hostility. The Spanish "civil war" and the Sino-Japanese conflict were areas where war had not been officially declared. Therefore, these countries placed large orders for military aircraft to the U.S. aircraft industry. American exports increased until 1938, when the law was redefined: war now included the bombing of civilian populations with no official declaration of hostile intentions. Even so, there were still records of contracts for aircraft and non-munition aircraft component sales to Japan as late as 1939.[10]

The Neutrality Act passed in 1935 was repealed late in 1939. At this point, Germany, France, Italy, Great Britain, and other countries were in a declared state of war. National sentiment was moving away from isolationism towards support of the Allied forces. Many in the United States secretly feared that Germany would become a threat to the United States if it continued to gain power. As one German victory followed another, the U.S. repealed the Neutrality Act and allowed the sale of munitions to friendly nations. Orders from "neutral" countries also increased, as fear of spreading aggressions caused governments to actively invest in protecting themselves and their interests.

The aerospace market was booming in the United States. Most sales were exports, as the U.S. was still taking no official stand on their involvement in the war. But U.S. orders were still increasing. To allow the industry the space it needed to produce the required aircraft—and to ensure that U. S. orders would not take a back seat to the more profitable foreign orders—Congress eased the procurement laws and allowed contracting officers to negotiate contracts with industry. However, Congress did eliminate the cost plus percent profit option and replace it with a cost plus fixed fee. Profit then, was not a percentage of cost. It was fixed regardless of costs, and any project completed under cost did not receive the surplus as profit. While this plan did little in the way of providing cost reduction incentives, it did eliminate the risks to the company that were involved with experimental development. To compensate, Congress repealed the 10% profit limit on aircraft. However, it did impose an excess profits tax on defense contractors.

Even as production geared up, it was still inadequate to meet demand. The pre-war production processes for hand-made products were not feasible in the fast-paced, high-demand war time production. Production in lots was also a common practice in small volume production and, in special cases, used in large production. Lots were small batches of the same pieces that were moved through the same processes at the same time. This method allowed for the most cost-effective use of equipment and set-up times, but created a bottle-neck in equipment use. Parts were also manufactured in job shops. In this case, similar kinds of equipment were grouped together. This concept limited the travel of a part all over the production floor, but caused a bottle-neck in production flow. Neither were extremely efficient methods of large scale production.

As early as 1940, the aircraft companies found that their processes were insufficient to meet demand. Therefore, they began seeking new methods of manufacturing. Line production, common in other aspects of American industry, was new to the aircraft manufacturers. Although it took several years, by 1944 the major airframe and engine companies were operating a line production facility.

The spirit of cooperation from World War I was a key factor in the aircraft industry's ability to meet the high demand, including cooperation between prime contractors and their sub-contractors. This cooperation existed because there was little need to compete with one another—the demand was more than any one of them, or even all of them, could handle.

Furthermore, there was strong cooperation between both the Army and the Navy with their prime contracting company. Speed and efficiency were the orders of the day. Superior air power depends on manufacturing capacity, the ability to mobilize and expand these resources, and the cooperation between the civilian experts and the military personnel responsible for procurement.[11]

Even though the primary goal was to win the war, there was still time for political and bureaucratic warfare. Congress feared the greater freedom of the procurement officers would lead to corruption. As the aircraft production capacity increased and concern about the country's ability to meet its wartime objectives decreased, there was time to revisit procurement issues. Congress tried to remove the fixed fee contracting option and replace current fixed fee contracts with fixed price contracts. The aircraft companies were not willing to accept Congress' proposal. Eventually, Congress relented since changing a contract's terms after award would be breach of contract.

Additionally, Congress set forth the Small Business Act. This act was to aid small businesses, hurt by the depression and unable to win military contracts due to lack of size and experience. This requirement angered military procurement officers, who felt their authority and flexibility were limited by this act. The officers feared that the structure of this act gave too much power to the small business board responsible for organizing the small businesses who were interested in military contracts. The military was justified in its concern, as many subcontracts were awarded to companies unprepared and unable to meet military requirements. Their inability to operate efficiently under military regulations seriously hindered the war effort and increased the cost to the government due to rework and re-negotiation of small business contracts.

1.4 The Cold War and the Nuclear Age

The period from 1945 through the early 1990's was one of extreme conflict, rapidly changing priorities, and significant upheavals in the military's role in the new U.S. political structure. The national security goals underwent a variety of changes, ranging from a state of extreme preparedness for imminent conflict to isolationism.

Traditionally, the United States had always disbanded its military forces after war. The national abhorrence to a standing army in peacetime was based in the fear that such an army would infringe upon the rights of civilian personal liberties. However, after two world wars officials considered such a demobilization policy to be contrary to the best interests and even the safety of the United States. As General H. H. Arnold, Chief of the Air Forces said, "It is of the utmost importance that our first line of defense, in the air, must be ably manned and fully supplied with modern equipment. The United States must be the world's first power in military aviation."[12]

After the war, the military took a long and hard look at its procurement processes. The Congressional pre- World War II regulation requiring competitive bidding did not appear to guarantee appropriate prices or performance as legislators believed. The regulation ultimately forced the military to accept the lowest bid regardless of the procurement officer's judgment of the quality of the system or the company's ability to deliver. Additionally, Congressional treatment of the aircraft industry as a free market—not regulated one—led to many decisions which did not produce the expected results in the monopsonistic market.

The Congressional Procurement Act of 1947 was drafted at the end of the war when all of the procurement officers' emergency powers came to an end. The military was unwilling to operate under the restrictive procurement environment Congress had set up prior to World War II, so they requested reform. The military believed that if reform was enacted, Congress would be accepting the aircraft industry as a concentrated market and would be showing a willingness to trust the procurement officers professional capabilities.[13] However, the military needed to provide clear, cohesive arguments as to why such discretionary powers should be allowed during peace time. The three arguments[14] used were:

1. the coming peace was of an exceptional nature from that the U.S. had experienced prior to World War II (i.e. there would not be a large scale dissolution of military forces during this peace),
2. the enhanced powers of the procurement officers promoted, rather than hindered, the economy, and
3. Congress would be able to hold the procurement officer accountable for their actions.

The new procurement bill was drafted by the Army and the Navy then sent to Congress. The bill required contract award through competitive bidding, but allowed for exceptions where negotiated contracts could be substituted. Some examples included the procurement of items where design and quality considerations were paramount to the product, or on research and development projects where costs included facilities and equipment. The previously used option of the delivery of a prototype for competition evaluation was abandoned, as the increasing complexity of aircraft made the prototyping competition cost prohibitive.

The only major modification to the procurement bill limited the power of allowing negotiated contracts to the Secretary, Under Secretary, or Assistant Secretary of Defense. In addition, these decisions had to be supported by written statements and procurement officers were required to keep records of the project for six years. These restrictions would facilitate future congressional audits.[15]

In the post-war world, the significant differences in the political and social goals between the United States and the USSR caused excessive mistrust between the two states. Soviet leaders were convinced that capitalism sought the destruction of the Soviet system. Likewise, the United States, with its long-standing suspicion and dislike of communism, believed that the USSR was intent on world conquest and the destruction of capitalism everywhere.

The distrust between these two states inevitably involved the two parties in a land war in Korea in 1950. Communist North Korea, supported by Communist China and the Soviet Union, invaded democratic South Korea. The United States' inability to win the war resulted in a negotiated end to hostilities and the re-establishment of the political structures and territorial controls to those that existed before the invasion. This confrontation solidified the American public opinion of communist hostility that made normal relations with any Communist government impossible. The United States developed a philosophy of "containment," a term coined by U.S. diplomat and Soviet expert George Kennan. Containment involved the U.S. curtailing communist expansion by responding immediately to any move the USSR might make. In retaliation, the USSR adopted a similar national policy. To carry out these national objectives, both sides built their forces at alarming rates. Each wanted to be "stronger" than the other.

Before the growth of outward hostilities between the U.S. and the USSR, the U.S. emphasis on the nuclear superiority as a deterrent to war drew attention away from the necessity for conventional forces. The Air Force was simply required to provide cover and support for the bomber, which was simply required to drop its cargo at the desired location. This National Security strategy was partly to blame for the decline in conventional U.S. forces. However, when the Soviet Union acquired nuclear capabilities, nuclear weapons were no longer a deterrent to war. Therefore, a new strategy was developed: that of mutually assured destruction. To deter the enemy from using nuclear weapons, the enemy had to believe that they would be thoroughly destroyed in retaliation. As all sides were "persuaded" by this strategy not to use their nuclear weapons, conventional forces had to increase to keep a nation from having to utilize nuclear capabilities.

This rate of nuclear weapon growth continued on both sides until 1963, when the Nuclear Test Ban Treaty was signed. This was a turning point in the Cold War. It demonstrated that both the U.S. and Soviet leaders realized the nuclear arms race was a costly and risky struggle. The armament escalation increased both the danger of real war and the likelihood of rash action by either side that would lead to large scale devastation.

However, the arms race continued in conventional weapons. The U.S. became involved in the Vietnam War, while still operating under the "containment" policy. However, the poor management of the war, its lack of specific objectives, and limitations on useable force generated a great deal of resentment among the citizens of the United States, primarily the younger generation. The belief that not only was the Vietnam war wrong, but all war was wrong and the U.S. should completely dismantle its military gained public popularity.

While the Cold War arms race funneled millions of dollars into the defense industry, even after the nuclear weapon ban of 1963, there was a decrease in the amount spent on aircraft. The advent of missiles provided a less costly, more appealing weapon as there was no need for a human pilot. The aerospace industry adapted remarkably to the rapid shift in priority. Most major aircraft companies were able to modify their plants to produce missiles. The same was true during the shift to the space age. The aerospace industry, already experienced in dealing with government purchases and long term programs, had the knowledge and capacity to supply missiles, aircraft, and spacecraft.

Even during the height of the Apollo era, with national sentiment based on "beating the Russians", there was considerable public concern that such funds might better be spent elsewhere. While this may not have been a first in the history of the aircraft industry, it was the first time since World War II where such ideas became dominant public opinion. This shift in public attention combined with the inherent American distrust of standing armies—any standing armies—was one of the reasons for increasing investigations and publicity regarding fraud, waste, and mismanagement within the defense aerospace industry.

1.5 The Modern Military Aircraft Industry

In 1986, the U.S. had military obligations in over 60 foreign countries. That number increased when President Reagan pledged support for anti-Communist insurgents in the third world.[16] In 1989 the Berlin Wall fell. In 1991, the USSR splintered into the Commonwealth of Independent States. Also, terrorism was on the rise from 1968 as a method to try to force political change.

The political environment the world had been used to was changing rapidly. Due to this complexity, the United States was unable to develop a stable national security policy. The U.S. continually over-committed its military capability. By then end of the 1970's, the U.S. was spending approximately $150 B on defense, which did not provide enough funds to meet the Congressional and Presidential military goals.

When President Ronald Reagan entered office, he began a military buildup attempting to bring the U.S. military closer to meeting its expected objectives. Over the course of six years, an extra $1 trillion was spent on defense. However, by 1988, the defense budget needed an additional $400 B per year just to pay for programs which had already been approved. This corresponded to a 30% annual increase in funding.[17]

The increasing defense budget during this short time put tremendous pressure on other programs. As shown in Figure 1.2, non-defense expenditures had been increasing drastically since the Korean War.

Even with the large increases in the late 1980's, the defense industry is no longer the dominant expense in the federal budget. In the 1950's, defense accounted for 50-60% of the federal budget and entitlements (Social Security, Medicare, etc.) accounted for 20-30%. By the early 1970's, the percentages were about equal and in 1996, defense was down to 16% of the budget and entitlements were nearly 60%. Figures 1.3 and 1.4 show the budget breakdown.

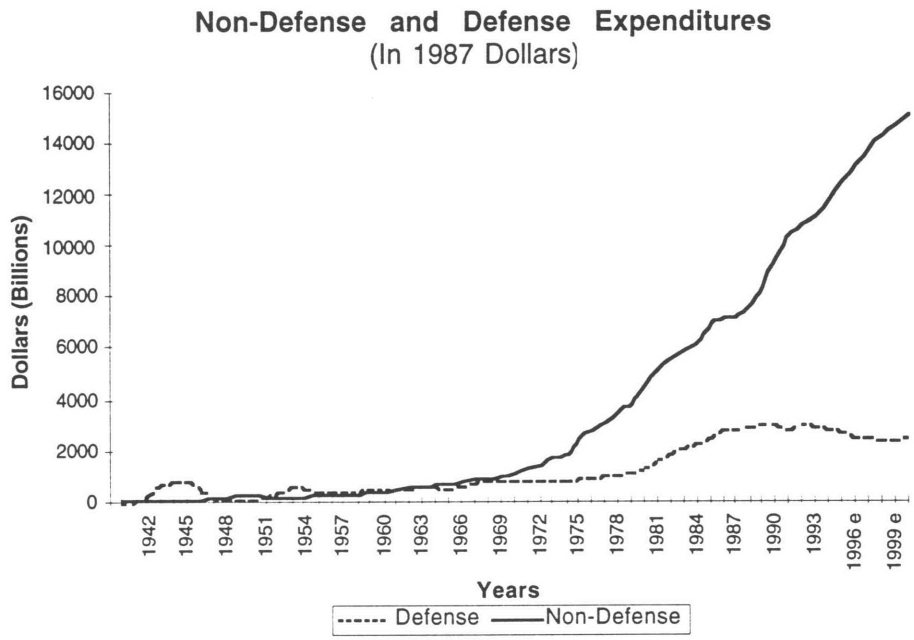

Figure 1.2 **Total U.S. Outlay per Fiscal Year.** The values have been adjusted for inflation to 1987 dollars.

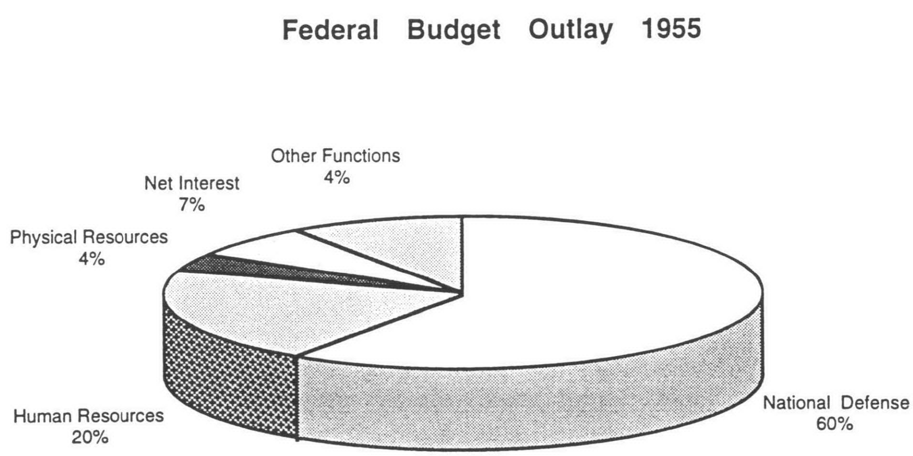

Figure 1.3 **U.S. Federal Budget FY 1955.**

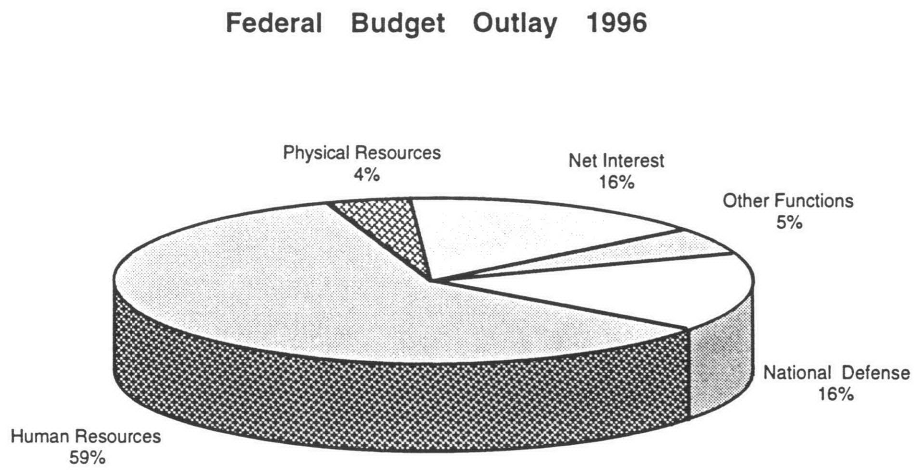

Figure 1.4 U.S. Federal Budget FY 1996.

Despite the fact that entitlements now dominate the federal budget, military spending has been the first area for budget cuts. Entitlements are considered sacrosanct in the current political environment. While Medicare and Medicaid reform have become recent topics of debate and the ability of the current Social Security to meet its objectives has been questioned, there have been no funding cuts in any of these programs. The military spending program, as the second highest in the budget, has taken the brunt of the responsibility to balance the federal budget.

The media reports of outrageous expenses for every day items, excessive cost overruns on overall projects, and the inability of companies to meet their scheduled deadlines has fueled an increasing number of investigations into the military procurement system. Rather than studying the problems in the system, quick fixes have been instituted—usually involving additional layers of inspection, audit, and control to ensure that the government is not, for example, charged $1,000 for an Allen wrench. These hasty reforms have increased the levels of oversight and micro-management on a project, increasing the cost of maintaining programs.

Meanwhile, the instability of the national military policy has caused requirements on current defense projects to change frequently. These changing requirements increase the time and money required to complete a project, since completed development work may need to be scrapped as a result of the new requirements. Cost overruns and failures to meet schedules combined with the uncertainty of the project's mission compels Congress to cut funding on the project, further delaying the completion date as less work can be completed in a given fiscal year.

However, to put the military weapon systems into perspective, Figure 1.5 compares the development cost overruns of several military, commercial, and other government programs.

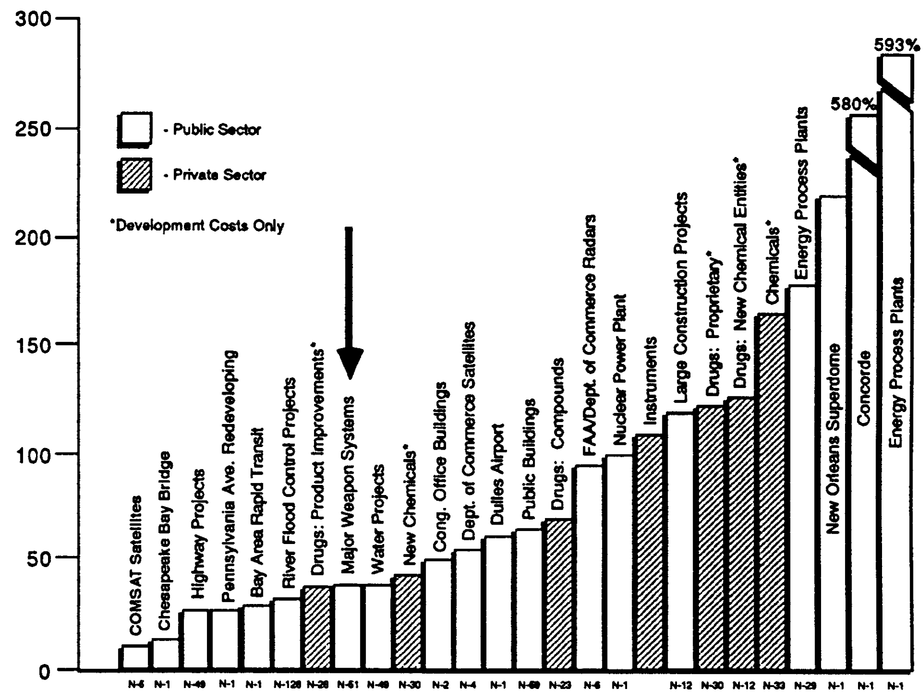

Figure 1.5 **Percent Cost Overruns of Major Projects.** These values have been adjusted for quantity and inflation. The N values along the horizontal axis are the number of cases in each group.[18]

The cost overruns of the average public construction project is about 40%. For the Senate Office Building or the Dulles Airport, cost overruns are 75%, and the New Orleans Superdome overran by 200%. For a project of comparable complexity to a military aircraft, the Concorde and the Trans-Alaskan Pipeline, went over budget by nearly 600%. A major military weapon system averages less than 50% cost overrun.

However, the question remains: What can be done to decrease the cost and time involved in developing a military aircraft? The following chapters describe a System Dynamics model of the development of a military project. This model indicates several areas identified by research at MIT's lean Aircraft Initiative as potential areas for improvement in the aircraft industry. The impact of process improvement practices on the interaction between the government and industry in the procurement of an aircraft will show the expectation of lean performance. Further, sensitivity analysis will indicate the variables that most strongly impact the performance of the government-industry partnership.

References

[1] Simonson, ed. The History of the American Aircraft Industry. p.25.
[2] Simonson, ed. The History of the American Aircraft Industry. p. 47.
[3] Simonson, ed. The History of the American Aircraft Industry. p. 84.
[4] Simonson, ed. The History of the American Aircraft Industry. p. 87.
[5] Kaufman. In the Procurement Officer We Trust. p.25.
[6] Simonson, ed. The History of the American Aircraft Industry. p. 86.
[7] Kaufman. In the Procurement Officer We Trust. p.25.
[8] Simonson, ed. The History of the American Aircraft Industry. p. 99.
[9] Biddle. Barons of the Sky. p. 244.
[10] Simonson, ed. The History of the American Aircraft Industry. p. 108.
[11] Holly. Buying Aircraft. pp. 4-5.
[12] Simonson, ed. The History of the American Aircraft Industry. p. 171.
[13] Kaufman. In the Procurement Officer We Trust. p. 49.
[14] Kaufman. In the Procurement Officer We Trust. p. 49.
[15] Kaufman. In the Procurement Officer We Trust. p. 53.
[16] Gansler. Affording Defense. p. 29.
[17] Gansler. Affording Defense. p. 1.
[18] Gansler. Affording Defense. p. 5.

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CHAPTER 2

SYSTEM DYNAMICS MODELING

The government-industry military procurement system is a complex dynamic process with many constantly changing inputs, outputs, and internal functions. It is not surprising that the "quick fixes" implemented over the years—attempting to contain costs and control fraud and waste—have been at best ineffectual and at worst inhibitors to streamlined operations. Without considering the entire system—consisting of any interaction considered to impact the dynamic under investigation—and understanding its inherent behaviors, any practice implemented is likely to cause undesired effects.

System Dynamics is a method of studying the behavior of systems to show how decisions, policies, structures, and delays are interrelated to influence growth and stability.[1] A System Dynamics model is a collection of multiple feedback loops designed to describe the behavior of a particular problem. These models are useful because, while the human mind is good at analyzing and understanding the structure and framework of a system, it is not adapted to interpreting the behavior of that system.[2] Most often, managers, engineers, and other people make decisions based on their mental models—how they mentally perceive the system. However, since these models are often subconscious they are subject to the fluctuations of the daily crises of the system. These models also include leaps of logic and unclear connections between issues. While these mental models are important—they influence the daily decisions regarding the system—they can inhibit progress if the mental model does not include or misinterprets important issues.

2.1 The Modeling Process

The strength of the System Dynamics model is twofold. First, it is a model constructed with the input of several points of view. The more individuals included in the development of the model, the more likely the resulting model will capture the important behavior of the actual system. While increasing the number of inputs can increase complexity, through the modeling process this complexity can be reduced through an iterative modeling process which indicates some variables thought to be important actually are not. Further, increasing the number of people involved in the modeling process will make each individual feel he or she has added the dynamic which concerns their area of expertise. Second, it is a written record of the interactions between practices, therefore it is not subject to the daily fluctuations which mental models experience. The model is an independent entity that operates only on the programmed interactions and input data. Jay Forester, the pioneer of System Dynamics, explains that the most important difference between mental models and dynamic computer models lies

> "...in the ability to determine the dynamic consequences when the assumptions within the model interact with one another. The human mind is not adapted to sensing correctly the consequences of a mental model. The mental model may be correct in structure and assumptions but the human mind...is apt to draw the wrong conclusions...It usually happens that the [mental] system does not act the way the person anticipated [when the computer model derived from the mental assumptions is run]. Usually there is an internal contradiction between the assumed structure and the assumed future consequences."[3]

2.1.1 Defining the Problem

The first step in the modeling process is to define as clearly as possible the problem the model addresses. It is important to be very specific so the simplest model possible can be constructed, yet still capture the important dynamics under investigation. Most often, System Dynamics models begin with a subsystem of the larger problem. Usually this subsystem model provides enough insight to the problem to stop at this stage. However, if one desires a larger view of the system, one can expand upon the smaller model to incorporate a wider range of issues. However, as the size of the model increases its complexity also increases. This complexity increases the difficulty of tracing individual variable interactions and may not contribute sufficiently to the output to warrant the additional complexity. The goal of a System Dynamics model is to be a simplistic as possible while capturing the dynamics important to overall performance.

2.1.2 Determining the Important Variables

What variables are important in describing the problem that was defined? At this point in the modeling process, all variables that are considered important should be listed. It is easier to later eliminate variables that are not as important as once thought to be rather than try to later add new variables.

A reference mode shows how the variable is expected to change over time. It is important to consider in this step the variable's time frame. For example, the short term investor considers a stock's performance over a period of days or perhaps weeks when making investment decisions. However, when considering a retirement account or a child's college fund, a time scale of years or perhaps decades is more important. The short term investor may go with a stock that has poor long range performance if he or she expects immediate improvements. The long term performance is unimportant, as the investor will pull the money out (presumably) long before the stock turns for the worse. However, the second investor is unconcerned with the large daily or weekly fluctuations of a stock (which were critical to the success of the first investor), as the payoff for him or her is far in the future. This is the time scale of the variable. When considering a variable, the time scale should begin far enough in the past to capture historical information and extend far enough into the future to predict potential future trends.

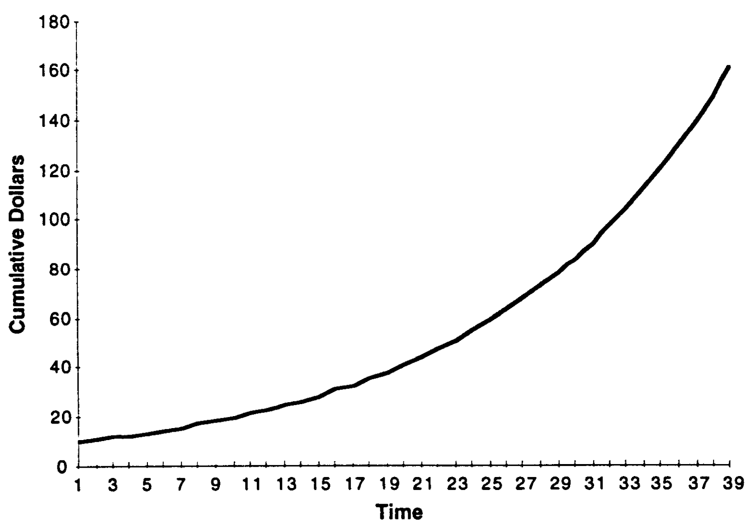


Figure 2.1 Reference Mode for Total Expected Funds vs. Time.

2.1.3 Developing a Dynamic Hypothesis

The dynamic hypothesis is simply what is thought to cause the changes in the reference modes from Section 2.1.2. For the reference mode in Figure

2.1, the underlying hypothesis is as more capital is invested, more interest income will be earned. This interest income, once reinvested, increases the capital available to invest. The actual speed at which this occurs depends on the interest rate at which the capital is invested.

A Causal loop is a representation of the feedback of the system. An arrow with a + indicates a positive interaction. A positive interaction is where an increase in the first variable causes an increase in the second variable. Conversely, a decrease in the first variable causes a decrease in the second. Succinctly, a positive interaction means the two variables move in the same direction, increasing or decreasing. This arrow is sometimes labeled "s" for the variables moving in the "same" direction. For example, as the capital invested increases, the interest income earned increases

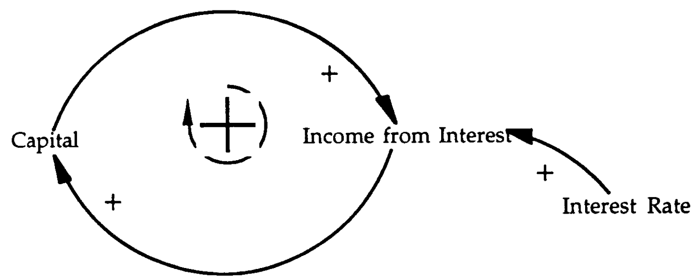


Figure 2.2 Positive Causal Loop: Capital Investment and Interest Income.

An arrow with a - indicates a negative interaction. This is where an increase in the first variable causes a decrease in the second variable, or a decrease in the first variable causes an increase in the second. A negative interaction means the variables move in the opposite direction. That is why the arrow is sometimes labeled "o" for "opposite". For example, consider the causal loop in Figure 2.3, a heating system. If a room is too cold, temperature increases cause the gap between the actual and desired temperatures (desired temperature - actual temperature) to decrease. Likewise, if the room is too warm the value of the gap is negative. A decrease in the room temperature will bring the gap closer to zero.

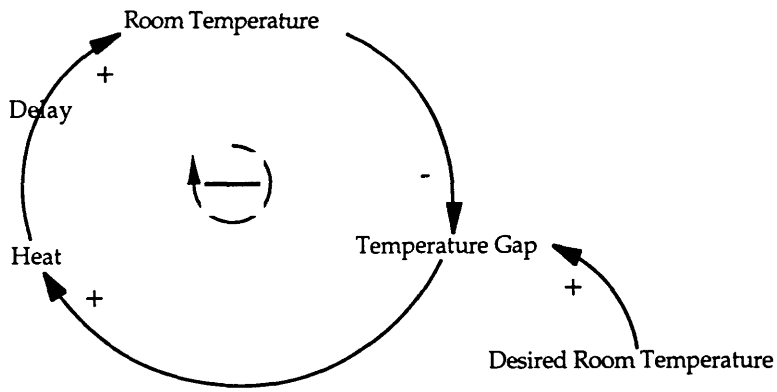


Figure 2.3 Negative Causal Loop: Heating System

The collection of positive and negative interactions create a feedback loop. A positive—or reinforcing—loop is one with zero or an even number of negative interactions. This loop tends to spiral out of control. Consider the extreme case of Figure 2.2. If the interest rate remained constant, the capital invested would cause an increase in the interest-earned funds. These interest-earned funds would increase the available capital, again increasing interest income. The funds grow exponentially, as show in Figure 2.4.

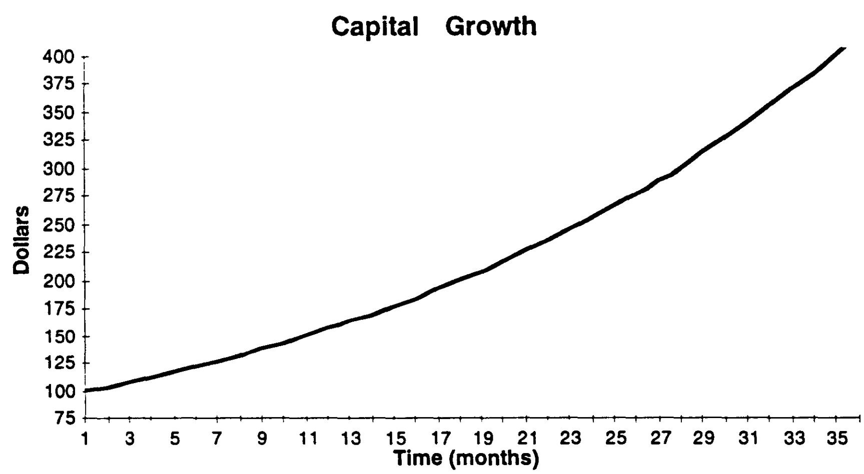


Figure 2.4 Capital Growth. Constant Interest Rate.

A negative—or balancing—loop, is one with an odd number of negative interactions. In Figure 2.2, if the room temperature is too low, the gap between the desired room temperature and the actual room temperature will increase, causing the heat to increase. After a delay, the increased heat will cause the room temperature to increase. Once the room temperature equals the desired temperature, the temperature gap will decrease, causing the heating to decrease. The result can be seen in Figure 2.5.

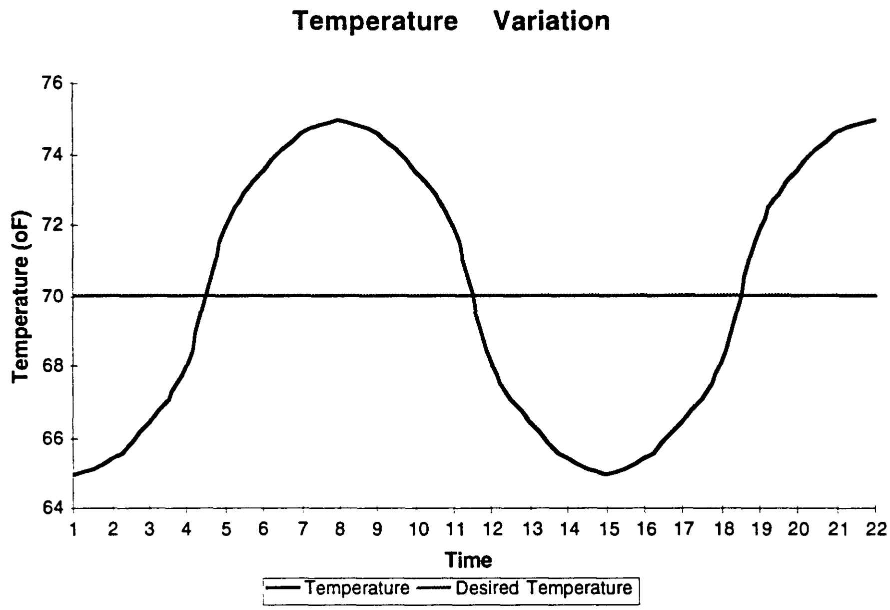


Figure 2.5 Room Temperature

Negative loops are desirable. These are the feedback loops that create stability in the system. The effect of changes implemented in a stable system are easier to identify. Changes implemented in an unstable system are likely to be lost in the rapid increase or decrease of the overall system.

As shown in this section, a causal feedback loop should be analyzed after its construction to be certain the theory behind the loop agrees with the reinforcing or balancing nature of the loop. However, causal feedback loops are not etched in stone. They represent a theory about the behavior of the system. In this step of the modeling process, the model builder asks many questions along the direction of the hypothesis in the process of creating a more useful model.

Figure 2.5 shows an interesting characteristic. The delay time between the heat turning on and the room warming up causes oscillation. When the delay is large, even after the heat itself has been turned off the temperature of the room will continue to increase as the extra heat from the heating element will pump into the room. Once the temperature drops too low, the heater will be turned on. But in the time required to reheat the now cool heating elements, the room will continue to lose heat. A very short time delay (or no time delay at all) minimizes or eliminates this oscillation.

2.1.4 Constructing the Model

Once the causal feedback loops have been constructed, the actual model can be built. The basis for the System Dynamics model is a stock and flow structure. A stock is a system state variable. It cannot be directly controlled, but is rather changed by the flows associated with it. The flows are controlled by policy based decision rules and are functions of time. The basic stock equation is

$$S_t = \int_{t_0}^{t} (F_i - F_o)dt + S_{t-1} \qquad \text{Equation 2.1}$$

where

S_t is the value of the stock at time t,

F_i is the sum of the inflow rates,

F_o is the sum of the outflow rates, and

dt is the time step.

The System Dynamics model is built based on the hypotheses solidified in the causal loop diagrams. This is the step where all of the impacting variables are included. For example, Figure 2.6 is a portion of the model that describes how the current schedule is measured.

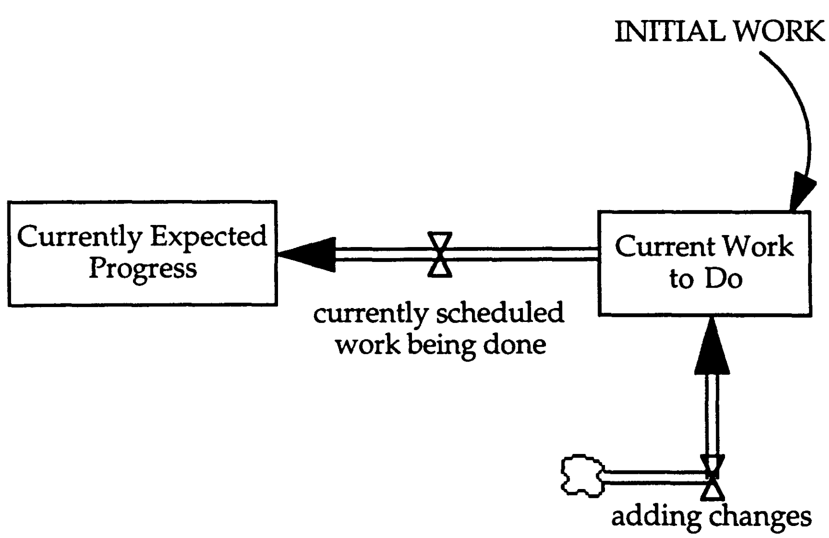


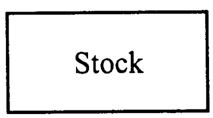
Figure 2.6 System Dynamics Model of Current Schedule Progress.

The stock of Current Work to Do has an initial value of Initial Work (the total amount of work required to complete development). Current Work to Do increases as the flow Adding Changes adds work to the stock (inflow rate). Current Work to Do decreases as Currently Scheduled Work Being Done moves work from Current Work to Do to Currently Expected Progress (outflow rate). As work is completed, Currently Expected Progress increases. This is the measure of the amount of work that the current contract schedule plans to be complete at any given time. In this example, the stock equations are

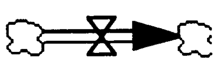
$$\text{Current Work to do} = \int_0^t (\boldsymbol{adding.changes - currently.sceduled.work.being.done})dt \qquad \text{Equation 2.2}$$

$$\text{Currently Expected Progress} = \int_0^t (\boldsymbol{currently.scheduled.work.being.done})dt \qquad \text{Equation 2.3}$$

Before this analysis continues, the symbols used in a System Dynamics model must be defined. These symbols are:



Any variable contained in a box is a stock. A stock is an accumulation—a variable that changes only over time. For example, if a snapshot were taken of a system, a stock is anything that could be measured by size, number, or intensity in that snapshot.



A Flow is a variable that directly changes the value of stocks as a function of time. The arrow of a flow indicated the flow direction.

A valve determines the rate of flow.

A cloud indicates a source or a sink that has not been explicitly modeled.

CAPS — A variable in all capital letters indicates the variable retains a constant value throughout the simulation.

Italics — A variable in italics indicates the variable is a graphical relationship. The variable takes an input and has an output dependent upon the particular non-linear relationship of the function. See Appendix A for examples of the functions used in this model.

Others All other variables are in lower case letters and represent intermediate calculations within the model.

2.1.5 Testing the Model

Once the model has been constructed, it should be tested for robustness. For example in Figure 2.6, what would happen if Current Work to Do was zero? Logically, Currently Scheduled Work Being Done should also be zero (if there is no work to do, there can be no work being done). Also, the Currently Expected Progress Stock should not increase. Several possibilities such as these should be tested to ensure that the model developed can handle real-world variations and possibilities.

2.2 The Output

Determining which variables are to be the model's output is very important. These will be the key variables whose performance the model seeks to improve. There selected variables should capture the important dynamic of the model while still demonstrating other important inherent behaviors.

2.2.1 Calibration

While the model produced by the System Dynamics analysis—or any modeling method—is a representation of the actual system not reality, it is still important to calibrate the model against real world data. Calibration is an iterative process that compares the model output to actual project data. This ensures the variables with values that do not change over time (constants) and functions obtained from observation and logical analysis effectively simulate reality to improve model performance and accuracy.

2.2.2 Sensitivity Analysis

The sensitivity analysis seeks to determine the impact of individual variables on the output of the model. A change of 10% of a variable which strongly impacts the dynamics will yield a much larger change in the model results. Likewise, a change in a variable that weakly affects the model output will cause a small change in the results.

The results of the sensitivity analysis will indicate the strong "key" variables. These variables will be the areas that should be further investigated to yield the most results for effort invested in improving performance.

2.3 Summary

This chapter has described the theory behind System Dynamics modeling. In the following chapter, this theory will be applied to the government-industry procurement problem. The causal loop structure and the resulting stock and flow dynamic model will be described and evaluated.

References

[1] Forrester. Industrial Dynamics. p. vii.
[2] Forrester. Counterintuitive Behavior of Social Systems. p. 7.
[3] Forrester. Counterintuitive Behavior of Social Systems. p. 9.

CHAPTER 3

THE MODEL

The consequences of increasing military aircraft prices and of decreasing military procurement budgets have become evident over the last few decades. As shown in Figure 3.1, the real price of aircraft has increased exponentially while, as shown in Figure 1.3 and 1.4, the percentage of the federal budget spent on defense has declined. The long term consequence of this trend could be that a single military aircraft may exceed the entire military budget, a circumstance which would dramatically reduce—or even make impossible—the ability of the United States to achieve critical military missions.

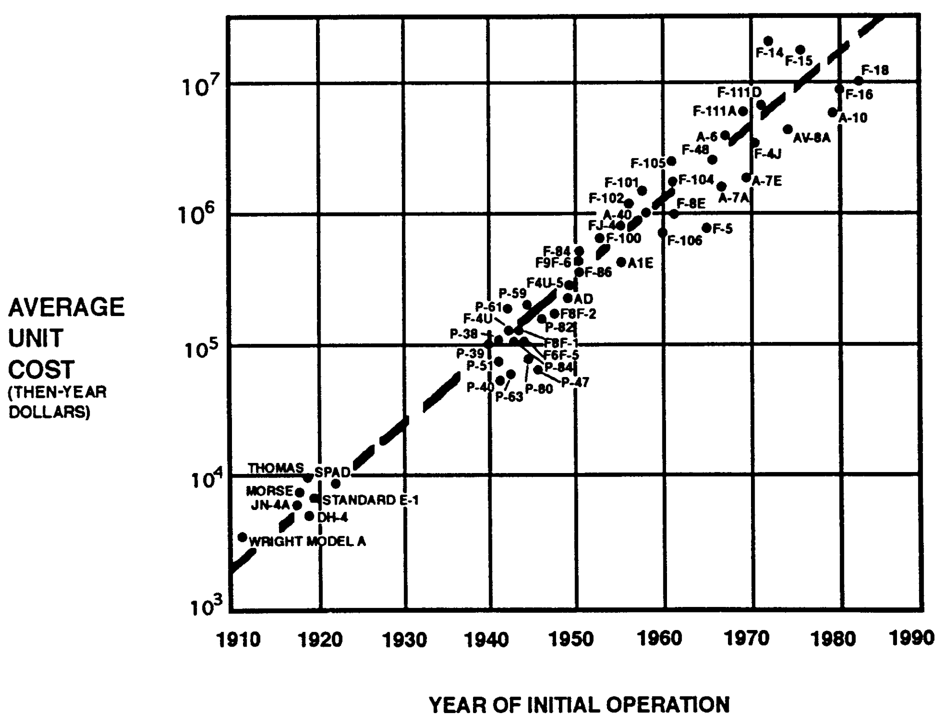


Figure 3.1 **The Rising Real Cost of Aircraft. The real unit cost of aircraft on a logarithmic scale vs. time. The rate of increase is a factor of four every ten years with no ceiling in sight.[1]**

The following model has been developed in an attempt to capture the important interactions within the military procurement system. The behavior of the procurement system can be analyzed by characterizing these government-corporate interactions. Further, once successfully defined, the model can be used to investigate methods for improving the performance of the entire system.

As described in the previous chapter, the first step in developing a System Dynamics model is to determine the scope of the problem to be addressed. For this model, the problem is defined as:

> What interactions between the government and industry cause an increase in the time and cost to design and develop a military product?

3.1 Preliminary Development—Reference Modes

Recall that reference mode is intended to describe the behavior expected from the model. The reference modes in Figures 3.2 and 3.3 show the expected changes in cost and time of development. Also presented are the "best" or improved and "worst" or pessimistic cases for each reference mode.

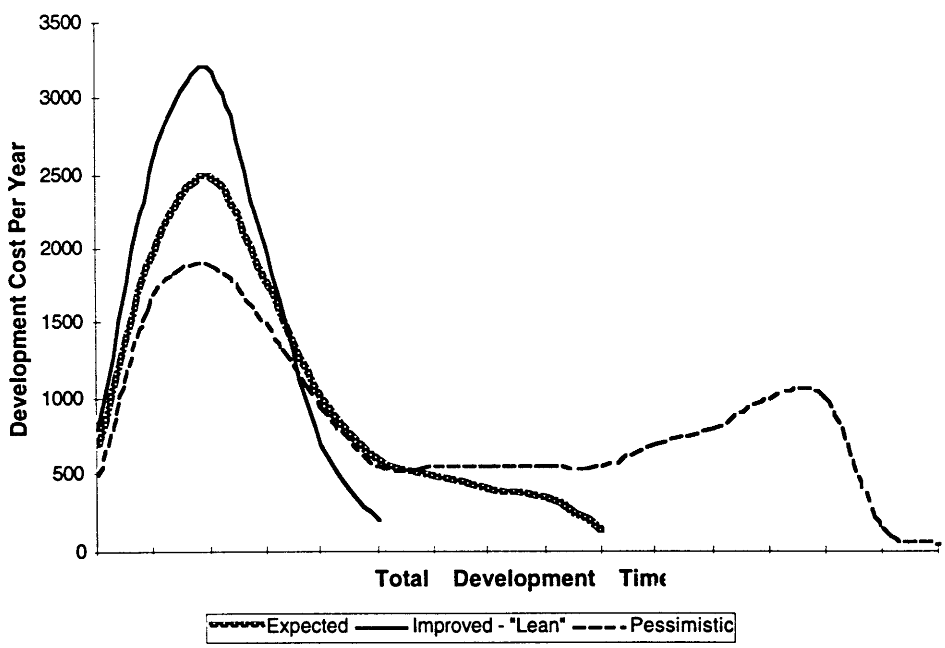


Figure 3.2 Cost of Development Per Fiscal Year. Reference mode of expected changes in the optimistic case, pessimistic case, and most likely case.

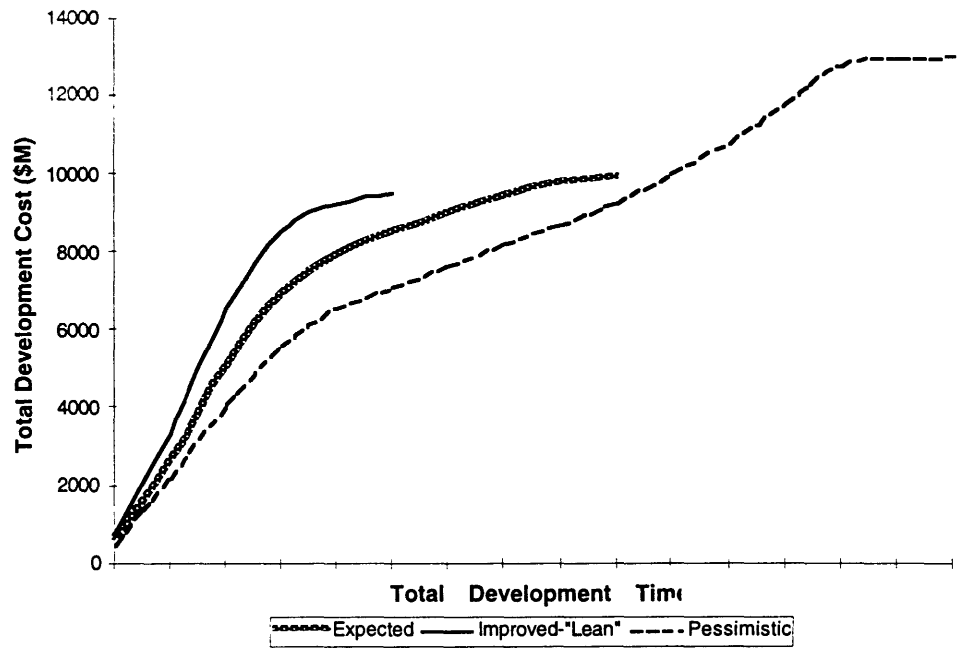


Figure 3.3 Cumulative Cost of Development. Reference mode of expected changes in the optimistic case, pessimistic case, and most likely case.

3.2 Development of the Model Structure

The development of this model is based on three main causal loop diagrams. The first is the Government/Congressional Expectation loop. This loop, shown in Figure 3.4, describes Congressional expectations of project funding changes.

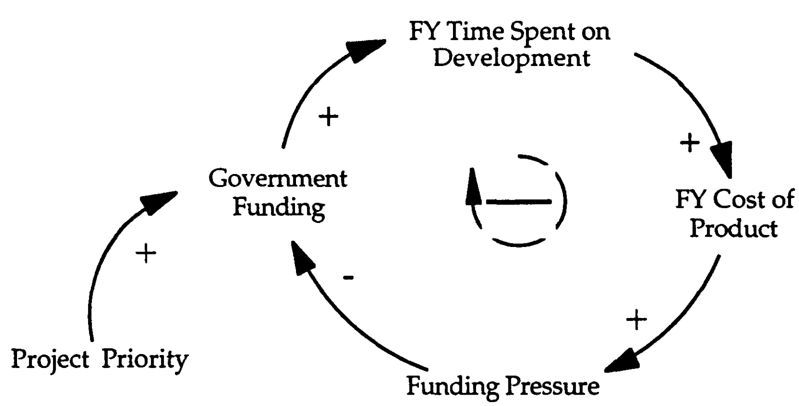


Figure 3.4 Government/Congressional Expectation Loop.

When government funding on a project decreases for any reason, the company will spend less time developing the project that year. Depending on the type of contract, companies usually spend only what is funded to them. Therefore, with a smaller budget the company accrues fewer development expenses that year. The decreased cost in the given fiscal year decreases the funding pressure—funding pressure is high when the project is over budget and low when the project is on or under budget—which creates an incentive to increase federal funding (since funding was low to start, lobbying for more money would be more beneficial than lobbying for more money when funding is high).

Additionally, federal funding is influenced by an exogenous variable (a variable whose value is not influenced by the system)—priority. Priority represents the perceived need for a project with respect to other projects vying for government funds. When priority is high, the project is considered quite necessary, and funding is more likely to increase so the project is completed as soon as possible. However, if priority is low, the project is considered less vital, and the government is not as likely to increase funding. Funding usually decreases in favor of higher priority projects.

While this mental model at the federal level is an accurate representation of the actual events, Congress—as the controller of federal funds—rarely considers a time frame longer than one year. Since military aircraft development cycles are much longer than one year, Congressional funding changes usually have future effects on the project that Congress does not necessarily consider when changing a fiscal year's funding allocations.

Figure 3.5 shows the causal loop of the project from the company's perspective. As federal funding decreases in a given fiscal year, the company must spend time to re-baseline the project. Re-baselining is absolutely critical to show the government *why* the project went behind schedule, justifying Department of Defense requests for additional funding in the following year. The time required to re-baseline would otherwise have been spent on further development. Continuing the downward spiral, the decrease in funds decreases the labor hours the company can spend developing the project in the given fiscal year. Thus, the company is forced to spend a great deal less time on development in that year. Because the development work remains, that work must be completed in a following year, thereby increasing the total time required for project development.

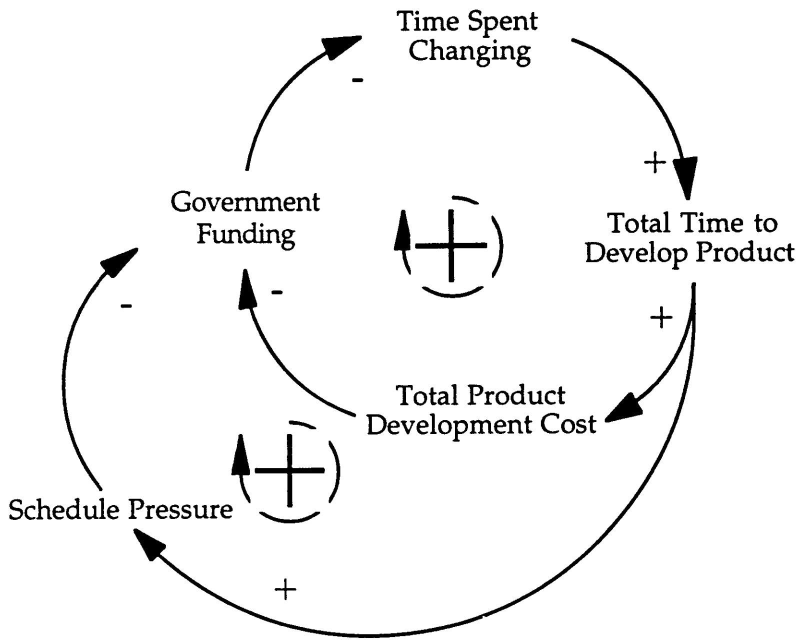


Figure 3.5 Corporate Progress Loop.

Further, the increased development time increases the overall project cost. This is due partially to inflation, which is consistently undervalued in military proposals because of political pressures. When inflation is high, Congress projects a downward trend for inflation to satisfy the public's desire for inflation decrease in the coming years. Therefore, Congress dictates the values for inflation for cost projections. In years where inflation is low, Congress will not project possible inflation value increases.[2] Thus, as previously stated, military projects are consistently undervalued because predicted inflation rates are lower than actual inflation rates. Another reason costs increase is due to the time involved in re-baselining after funding changes. These costs are never included in an original estimate because a potential contractor must optimistically hope to avoid them. Their proposal would likely be viewed less favorably during a competition as these additional expected costs prevent the contractor from submitting the lowest possible bid.

Therefore, as costs increase, funding is more likely to decrease in the following year for a program perceived as spiraling out of cost control. This is usually considered a sign of the project manager's and the contractor's inability to define and manage development. In addition, as the total time to complete the project increases, schedule pressure increases as the project falls behind its forecast. Again, the effect compounds as it is less likely federal funds will increase on a project behind schedule. In fact, federal funding is actually likely to decrease due to the perception of project mismanagement.

The third causal loop consists of the company's development process. In most projects the project planner does not sufficiently account for the impact of unplanned rework. Projects are composed of work to be completed, work in progress, and work already complete. Without consciously accounting for variations in the quality of work, the contractor essentially overestimates product quality and yield. As a consequence the project is not likely to be completed on schedule and on budget. Based on research by Pugh-Roberts, a System Dynamics Consulting firm, unplanned rework has been integrated into the Corporate Development causal loop structure of this model.

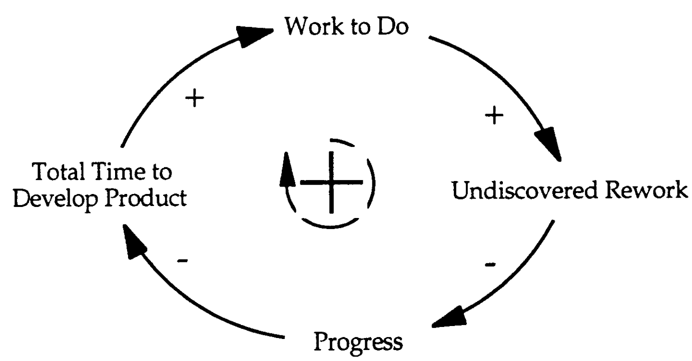


Figure 3.6 Corporate Development Loop.

Usually the project's development time is proportional to the amount of work to be completed. The larger the project, the greater likelihood that some required work will be done incorrectly and therefore increase the amount of rework required. As rework increases, the resultant decrease in actual progress increases the amount of time required to complete the project. This reinforcing loop is the principal explanation for why projects fall behind schedule.

Having analyzed these three causal loops, the policies identified in the causal loops must be converted into a dynamic model representing the system's behavior.

3.3 Model Boundaries

Recall that this model evaluates the behavior of a typical defense contractor and its interaction with the government during project development. To simplify the roles of multiple government agencies, this model merges Congress (as the controller of the government funds) and the System Program Office's project manager (as the distributor of funds) into a single entity—the "government." Similarly, the roles of the prime contractor (as the main project developer) and any sub-contractors (as supporting project developers) are also intermingled and will be referred to as the "contractor," "industry," or "company."

The time frame for this model is the average lifetime of a military aircraft development project; approximately five to fifteen years. The model begins with the awarding of a development contract and ends with the delivery of the first prototype. Further, the model design assumes that development occurs during a stable period with respect to military missions and political military expectations. This means once a contract has been awarded, its basic mission remains unchanged although project scope may be altered due to decreases in funding allocation.

The model assumes changes in project requirements result from decreases in funding from expected values. Falling behind schedule, going over the budget, and project priority cause funding changes. Therefore, if a project is always on schedule, on budget, and has no changes in priority, there are no changes in requirements and thus no additional work.

The model is cost constrained—i.e. the contractor can spend only what is funded. Funding can be in the form of funding allocations and percent over budget allowance. In a system where work is added, funding is decreased, and priority is the same as all other projects, the schedule is the first thing to slip to allow the project room to be completed.

Project priority is the relative measure of project importance. A priority of one means the project is as important as any other project competing for funding. This variable is explained more completely in Section 3.4.1.

This model is based on a fixed number of available employees. The profile of project funding allocation determines the maximum number of employees on the project. During the year of maximum funding flow, the maximum number of available employees are working on the project. However, the project is only charged for the amount of work done, not the number of employees designated. Therefore, the model funding results are likely underestimated.

Finally, please note that all financial information in this model is calculated in then-year dollars. This accounts for government projected inflation rates but not differentials between projected and actual inflation. However, the model does not account for project cost increases due to advancing technology.

3.4 Overview of the Model Structure

The model boundaries described above contain a collection of endogenous and exogenous variables. The endogenous variables are those whose values are influenced by the model, such as Funding Change. Conversely, exogenous variables such as the Initial Funding Allocation Stream, are those whose values cannot be directly influenced by the model.

3.4.1 Government Expectations

The core loop in Figure 3.4 describes the Congressional viewpoint of military product development. The stock and flow structure associated with this causal loop is shown in Figure 3.7.

Actual Funding is the stock of funds that have been allocated by the Department of Defense or by Congress (depending on the project classification—Congress controls funding on line item projects). This stock is adjusted by the flow of Funding Change and Over Budget Funding Allocation. Funding Change are the funds that have been approved by Congress for the given time period. Over Budget expenditures are those funds that account for the ceiling on a project's price contract. In this case, the ceiling has been limited to 5% above the allocated funds.

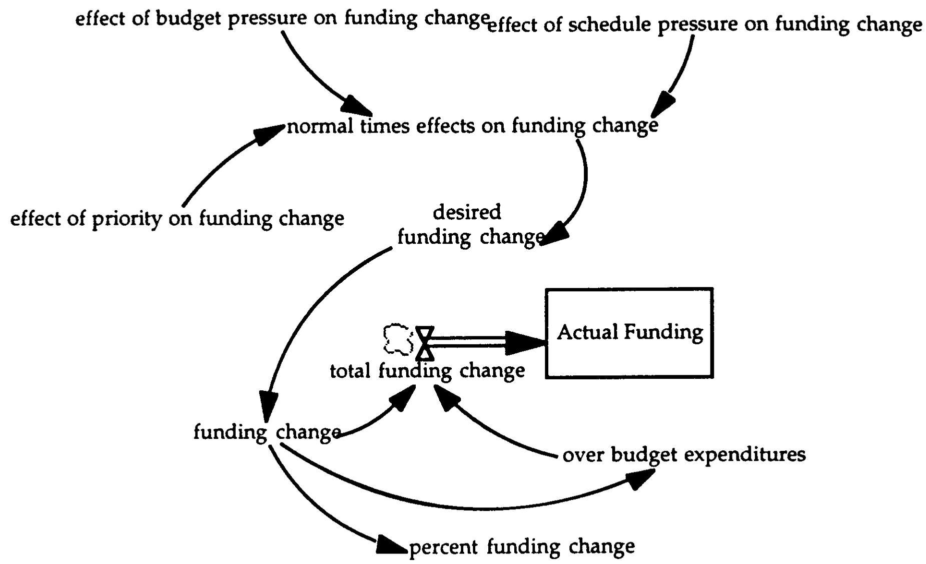


Figure 3.7 Government Funding Stock and Flow.

The 5% value of was derived from consulting with experienced government project officers. A value of 10% is usually the highest possible for a project. However, considering the current trends of decreasing military budgets, the Percent Over Budget Allowance is also decreasing. The values of 0%, 50%, and 100% were chosen as extremes (although 0% has become increasingly more likely.)

Funding Change is based on Desired Funding Change. Desired Funding Change begins with the value of the Initial Funding Allocation Stream—the funds allocated per year from the initial contract. This value is then increased or decreased based on the value of the Normal Times Effects on Funding Change. The Normal Times Effects on Funding Change is a compound variable with three components: Effect of Budget Pressure on Funding Change, Effect of Schedule Pressure on Funding Change, and Effect of Priority on Funding Change. These three variables are multiplied together to yield the value of the Normal Times Effects on Funding Change. This variable can have a value between zero and three.

As described before, Priority is a measure of the relative importance of the project. This variable can take on any value between zero and three. A value of three means that the project has a priority three times greater than other projects. A value of zero means the project is not a priority.

The Effect of Schedule Pressure on Funding Change causes the Desired Funding Change to decrease when the project is behind schedule. Likewise the Effect of Budget Pressure on Funding Change causes Desired Funding Change to decrease when the project is over its budget. Both of these variables can take on values between 0.32 and 1.

The value of 0.32 was derived from research of several projects funding flows: F-22, A-12, C-17, and F-18 E/F. This research showed when project funding was cut, it either decreased between zero and 60%, or it dropped to zero. Therefore, the Normal Times Effects lower limit was 40% (100% - 60%). In a constant priority project, only the Effect of Schedule Pressure and the Effect of Budget Pressure can decrease funding. Since the Normal Times Effects variable is the product of its inputs, the two inputs which change over time were constrained by a lower limit of 0.64—the square root of 0.4.

*Normal Times Effects = Effect of Budget Pressure on Funding Change * Effect of Schedule Pressure on Funding Change * Effect of Priority on Funding Change*

Equation 3.1

However, both the Effect of Schedule Pressure and the Effect of Budget Pressure are sums of their two inputs, one dependent upon the initial schedule and one dependent upon the current schedule. This caused the lower limit of the functions—both Schedule Pressure and Budget Pressure—to be constrained to half of the sum, or 0.32. The Budget Pressure Function decreases value as time progresses. Therefore, there is less emphasis on the initial budget later in the project and more emphasis on the current budget. The Effect of Schedule Pressure has a similar construction.

*Effect of Budget Pressure = Budget Pressure Fn (Time) * Initial Budget Pressure + (1 - Budget Pressure Fn (Time)) * Current Budget Pressure*

Equation 3.2

It should be noted that the effects of budget and schedule pressure cannot influence a funding *increase* (due to their upper limit of one). The only factor that can increase Desired Funding Change is Priority. Therefore, if a project is behind schedule, its priority with respect to other projects must increase for additional funding to be made available.

3.4.2 *Corporate Progress*

The Corporate Progress causal loop structure in Figure 3.5 has been converted to the stock and flow structure in Figure 3.8. The interaction between the prime contractor and the government during the EMD phase of the project is considered in this section of the model.

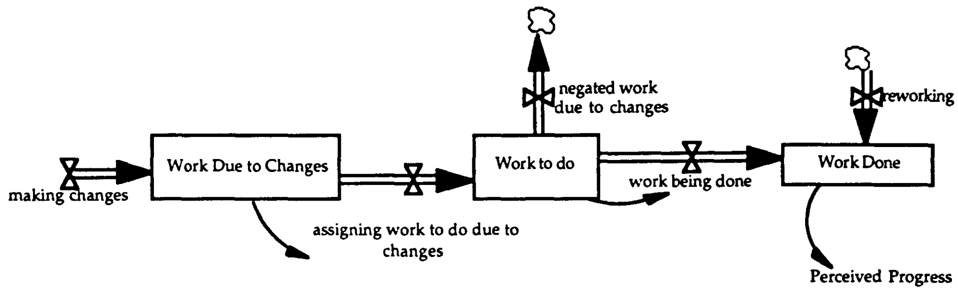


Figure 3.8 Corporate Stock and Flow Structure.

The stock of Work to Do has an original value of Initial Work—the total work required to complete the project at contract award. The Work to Do is modified as work is added (due to changing funding induced additional work) and subtracted (due to Work Being Done or Negated Work Due to Changes).

Work is added to the system when funding changes decrease government allocations below the expected value. This occurs because additional work is required to re-baseline the project and to make any project adjustments resulting from reduced funding. Each change must be analyzed and the work involved assigned to the appropriate area of development expertise. Assigning Work Due to Changes accounts for the work involved this step.

The sum of Work Done Right plus Undiscovered Rework (discussed in the following section) is referred to as Perceived Progress. When Perceived Progress is close to the project's anticipated progress, the project's schedule pressure is low. Similarly, when the project is on budget—as determined by comparing the Actual Project Cost to Initial Funding and Actual Funding—the project's budget pressure is low.

3.4.3 *Corporate Development*

This section of the model concerns the actual process of developing a project at the prime contractor site. As mentioned earlier, the roles of the prime contractor and sub-contractors (if any) have been intermingled for the purposes of this model. The important factors to consider are the amount of work that must be done and the resources required to complete that work.

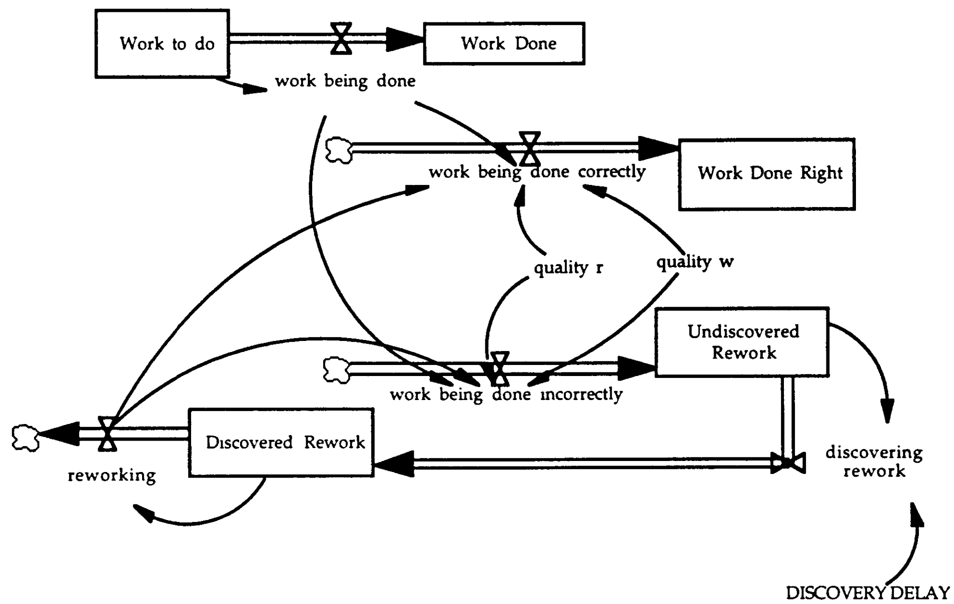


Figure 3.9 Corporate Development Stock and Flow Structure.

Work can be added to the system in the form of rework. Knowing that not all work will be completed properly the first time it is done, the Work Being Done Incorrectly is stored in the stock of Undiscovered Rework. Work remains in this stock until (after time has passed) the errors are discovered. Discovered Rework is stored in the stock until it has been reworked.

Work Being Done Correctly or Incorrectly is based on the amount of work that is being done at a given time and the quality of that work. Essentially, the higher the quality of work, the lower the amount of rework. However, even rework can be done incorrectly. Therefore, the model includes both Quality W (quality of work) and Quality R (quality of rework). The Quality R is assumed to be higher than the Quality W because employees are already familiar with the work and the reasons it needs to be corrected. Therefore, they are more likely to do work right the second time they attempt it.

Finally, the stocks of Work to Do, Work Done Right, and Discovered Rework can be decreased due to changes. As funding imposed changes are introduced in to the system, some of the work in the system will no longer be applicable to the project due to changing requirements.

The three stages where employees actually do work are Assigning Work Due to Changes, Work Being Done, and Reworking. The available work force is split between these three tasks as appropriate (i.e., workers will not be assigned to Reworking unless there is actually Discovered Rework). This allocation of resources is accounted for by three variables: Percent Time Assigning Work, Percent Time Reworking, and Percent Time Working. These three variables add to one at all times to ensure the allocation of workers does not exceed the actual pool of workers.

*Work Being Done = MIN (percent time doing work * effective people * productivity, Work to Do/dt)*

Equation 3.3

Equation 3.3 controls the Work Being Done. The MIN construction ensures that this function will do not more work than there is Work to Do. Therefore, if the normal rate of Work Being Done (Percent Time Doing Work * Effective People * Productivity) is greater than the work remaining in the stock at the current time period, the work remaining in the stock will be done. Therefore, the stock of Work to Do never becomes negative.

The rate of Work Being Done is dependent upon the employee's productivity (discussed in Section 3.4.5) and the amount of overtime they work (see Section 3.4.6). More productive employees accomplish more per hour. Employees who are working overtime also accomplish more based on the accomplishments of a standard work week. However, extended overtime influences other variables. Refer to Section 3.4.6 for further details.

3.4.4 Expected Progress

The project's progress is based both on the initial schedule and the re-baselined schedule. Figure 3.10 shows the stock and flow structure simulating project progress.

The Initially Expected Progress stock and flow determines the amount of person-hours of work that should have been completed at a given time. This is the project's initial schedule.

The project's Currently Expected Progress depends on the changes added into the system, taken out of the system, and the rate of doing work. These flows are, respectively, Adding Changes, Negated Work Due to Changes, and Currently Scheduled Work Being Done.

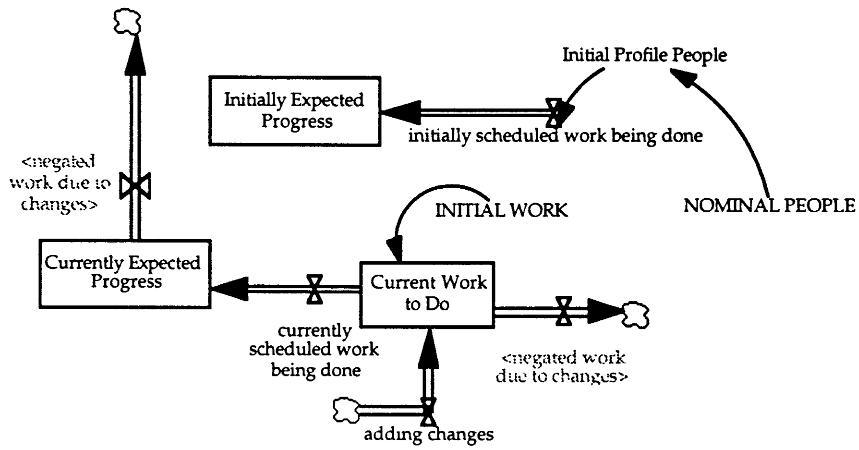


Figure 3.10 Initial and Current Progress Stock and Flow Structure.

The values calculated in this section are compared to the project to determine if the project is ahead of or behind schedule.

3.4.5 Productivity

Productivity is the effectiveness with which work is done. The more productive an employee, the more work he or she can complete in a given time period. This measure of productivity makes no assumptions regarding the quality of Work Being Done. Quality is discussed in Section 3.4.7.

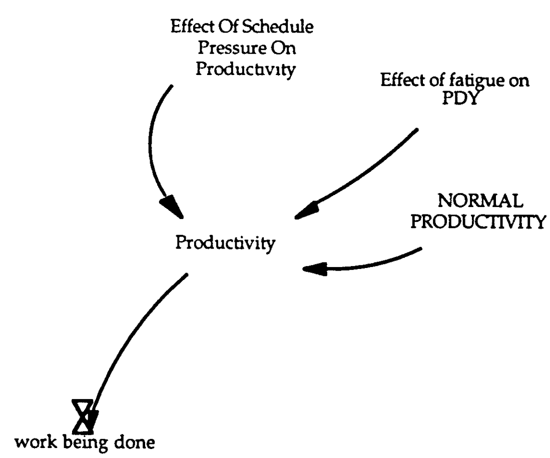


Figure 3.11 Productivity Stock and Flow Structure.

As shown in Figure 3.11, there are two major effects on productivity: Schedule Pressure and Fatigue. As Schedule Pressure increases (the project falls farther behind schedule), the employee's productivity increases. People tend to work harder attempting to meet a deadline. When the project is on schedule, there is no impact on productivity—the effect of schedule pressure is one. However, when the project is ahead of schedule, people are more relaxed which decreases their productivity slightly.

Productivity = Normal Productivity * Effect of Fatigue on Productivity * Effect of schedule Pressure on Productivity

Equation 3.4

Increasing Fatigue (which will be discussed in the following section) decreases an employee's productivity. When people are tired they tend to work more slowly, accomplishing less per hour than they could if they were not fatigued. however, decreasing fatigue below the standard value increases productivity slightly.

3.4.6 Fatigue

Employees become fatigued by working longer and harder than they are normally expected to. This model sets Fatigue at 1 as a base value. Increasing overtime causes increasing fatigue. Likewise, when people work less hours than standard, fatigue decreases. This structure is shown in Figure 3.12.

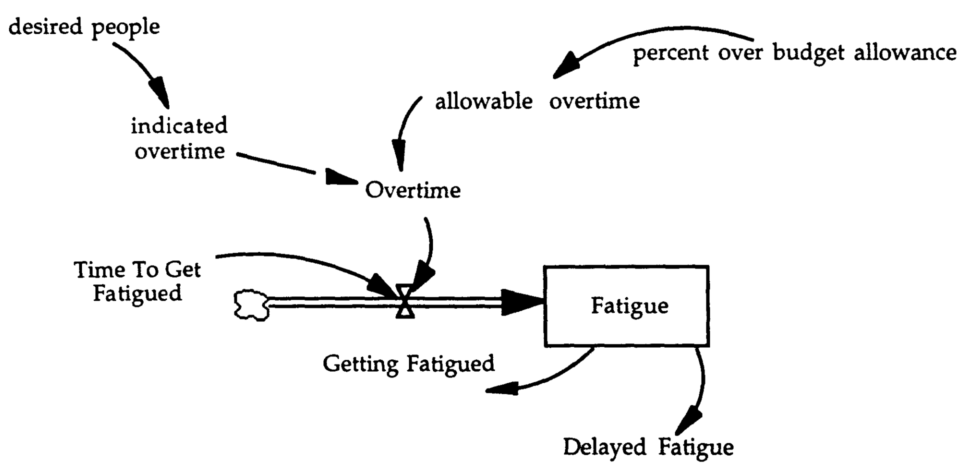


Figure 3.12 Fatigue Stock and Flow Structure.

The overtime allowed on the project changes as time progresses and depends upon two things: (1) how much overtime is desired, and (2) how much of the budget is available to fund overtime work. Indicated overtime represents the overtime necessary to bring the project back onto schedule. Allowable Overtime is the amount of overtime that can be afforded due to funding constraints. Overtime may take on a value from negative one and higher. A value of overtime below zero causes the amount of standard work time to decrease. This feature allows the amount of Work Being Done to respond to funding decreases. This scales down the number of employees on the project (or the percentage of their time that is spent on the project). An overtime value greater than zero indicates the percentage of overtime. For example, if Overtime was 0.4, employees would be working 40% overtime—an additional sixteen hours per week—for a total week of 56 hours.

3.4.7 *Quality*

Quality measures the percentage of work that is done correctly. For example, a quality value of 0.8 means that 80% of the Work Being Done is actually correct and 20% requires reworking.

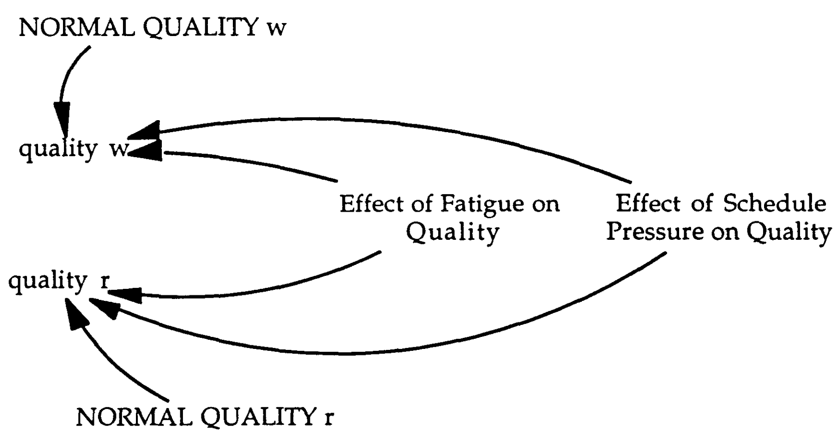


Figure 3.13 Quality Stock and Flow Structure.

As with productivity, there are two variables that affect the quality of Work Being Done: Schedule Pressure and Fatigue. A project behind schedule causes people to work faster, increasing Productivity However, when people work faster they tend to make more mistakes, decreasing the quality of their work. Fatigue causes the same effect, as employees who are run down tend to be less conscientious and make more mistakes.

As described earlier, the two measures of quality in this model: Quality W and Quality R—quality of work and Quality of rework being done. The initial quality of rework has been set higher than the initial quality for work.

3.4.8 *Financial*

This last section monitors the financial concerns of the model, excluding the government funding and the associated changes (refer to section 3.4.1 for details on government funding). The remaining financial concerns include Accruing Initially Funding, the Actual Project Cost, and the Initial Funding—the total cost of the project as stated in the contract (i.e. the initial funds allocated to the F-18 E/F prime contractor, McDonnell Douglas, were $3.7 B but these funds were not allocated all in one year).

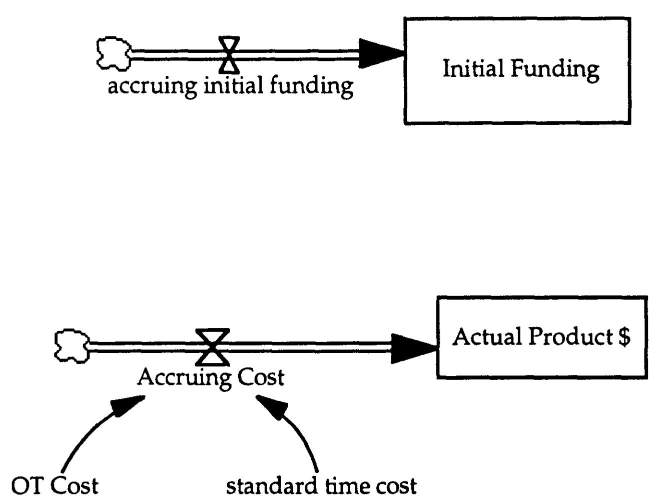


Figure 3.14 Financial Sector Stock and Flow Structure.

The Initial Funding stock accumulates funding based on the contract funding allocation profile. The stock of Actual Product Cost depends upon the number of overtime hours worked and the number of standard hours worked. These values are multiplied by the Development Cost Per Person Hour, a value derived from the Initial Product Cost divided by the Initial Work.

The details of each section outlined previously can be found in Appendix A. The constant values of the model are shown in Table 3.1. Figure 3.15 shows the model funding profile. The functions and a full listing of all variable equations can be found in Appendix A.

Table 3.1 Model Constant Values for Baseline Simulation

Variable	Value
Initial Funds Allocated	$10 Billion
Desirability	1
Changes per Dollar	1 person hour/ $30,000
Time Delay	2 months
Speed of Reworking	2
Nominal People	100
Initial Work	dependent upon funding profile
Normal Productivity	172 hours per month
Percent of Work Changed Due to Funding Change	25%
Discovery Delay	2 months
Speed of Assigning Work	3
Normal Quality W	0.8
Normal Quality R	0.9
Percent Over Budget Allowance	5%
Hours per Month	172 working hours/month
Time to Do Initially Scheduled Work	dependent upon funding profile

3.5 Calibration

The constants and functions of the model have been calibrated against actual project data from the F-18 E/F supplied by McDonnell Douglas. The information input into the model is shown in Table 3.2.

Table 3.2 F-18 E/F Calibration Constants

Variable	Value
Initially Expected Project Cost	$3.715 B
Time To Do Initially Scheduled Work	84 months
Initial Work	716,750 person-hours*
Changes per Dollar	15,000**

* Initial Work calculated from funding profile and Time To Do Initially Scheduled Work.

** Changes per Dollar value reached through iterative simulations.

Initial Work is calculated using the following equation:

$$\left[\frac{\textit{percent.funding profile.in year x}}{\textit{maximum percent.funding profile}}\right] * \textit{Normal.People} * \textit{Hours per.Month} * \textit{Months.per.Year}$$

Equation 3.5

From Table 3.3, the maximum percent funding profile is 28.8%.

Table 3.3 F-18 E/F Funding Profile

Fiscal Year	Contract Funding ($M)	Percent of Total	Actual Funding ($M)	Percent of Total
1992	97.4	2.6	102.4	2.6
1993	800	21.5	556.9	14.3
1994	1070	28.8	1,113.6	28.6
1995	1070	28.8	1015	26.1
1996	408.6	11	585	15
1997	186	5	247.2 *	6.4
1998	83	2.3	129.6 *	3.4
1999	0	0	140.9 *	3.6
Total	3715	100	3890.6	100

* estimated.

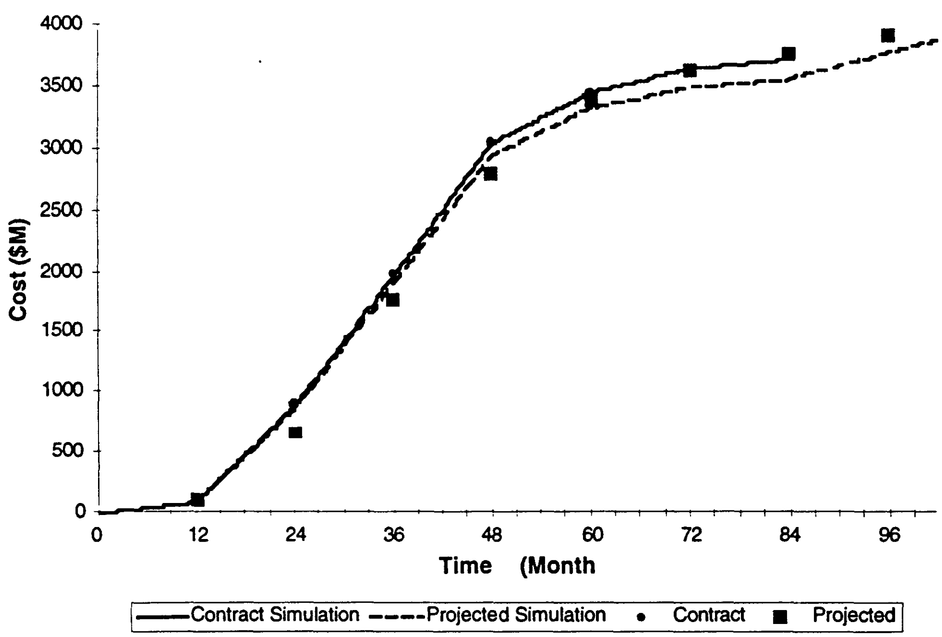


Figure 3.15 Calibration Results

The results of this calibration can be seen in Figure 3.15. The simulation of the contract yields a total cost of $3,714.6 million at 84 months. Based on the contract schedule of 84 months to complete the project at a cost of

$3,715 M, the model overestimates the completion time by 0.5 months and underestimates the cost by $0.4 M. The actual progress has projected a cost of $3,891 M at 96 months. The model's results for the actual case are $3,864 B at 101 months, underestimating cost by 0.7% and overestimating time by 5%. The cost values in each year for each series is shown in Table 3.4.

Table 3.4 Cumulative Project Cost, F-18 E/F Actual and Simulated Results

Year	Actual Contract (Million $)	Simulated Contract (Million $)	Actual Project (Million $)	Simulated Project (Million $)
92	97.4	96.6	102.4	95.95
93	897.4	895.2	659.3	870.4
94	1967	1965	1773	1907
95	3,037	3034	2788	2939
96	3,446	3,443.4	3373	3,315.8
97	3,632	3,629.1	3620	3,479.7
98	3,715	3,716.5	3750	3,552.2
99			3891	3,776
00				3,864
Total	3,715	3,716.5	3,891	3,864

3.6 Results

The initial results of this model have been separated into seven possible cases. These scenarios, detailed in Table 3.5, are the seven basic project possibilities.

The schedule case is the (optimistically) expected case. All work is done on schedule and there are no project changes or redesigns. However, most projects do not have all work done on schedule. Projects go through a series of unexpected rework cycles. (Expected rework cycles are included in the schedule). The two rework scenarios are with authorized overtime and without. But still in these cases there are no imposed project changes from external forces.

The next two cases consider changes that cause additional work to be added to the project. Again, this can be with or without overtime. The last two cases cover both changes and rework both with and without authorized overtime.

The results of these cases can be seen in Figure 3.16.

Table 3.5 **Model Simulation Cases.** Variables whose values have been changed are listed here. Any variable not listed retains the value listed in Table 3.1.

Simulation Name	Description	Variable Values	Completion Time (Months)*	Project Cost ($M)
Schedule	Contractor does all work on budget and on schedule.	norm quality w = 1 % over ,budget = 0 making changes = 0 normal times effects = 1	59.5	9.501
Rework - no OT	Contractor is not authorized for overtime to get back on schedule due to rework. Contractor does not experience changes in funding allocation.	% over budget = 0 making changes = 0 normal times effects = 1	84.5	10.41
Rework - OT	Contractor is authorized for overtime and receives additional funding to cover OT costs. Contractor does not experience changes in funding allocation.	making changes = 0 normal times effects = 1	80.75	10.8
Changes - no OT quality one	Contractor is not authorized for overtime to get back on schedule. Contractor experiences changes in funding allocation.	% over budget = 0 norm quality w = 1	59.5	9.501
Changes - OT quality one	Contractor is authorized for overtime and receives additional funding to cover OT costs. Contractor experiences changes in funding allocation.	quality w = 1	59.5	9.501
Changes - no OT	Contractor is not authorized for overtime to get back on schedule. Contractor experiences changes in funding allocation.	% over budget =0	113.25	10.4
Changes - OT	Contractor is authorized for overtime and receives additional funding to cover OT costs. Contractor experiences changes in funding allocation.		102.5	10.79

* The project is considered complete when 95% of the work has been completed.

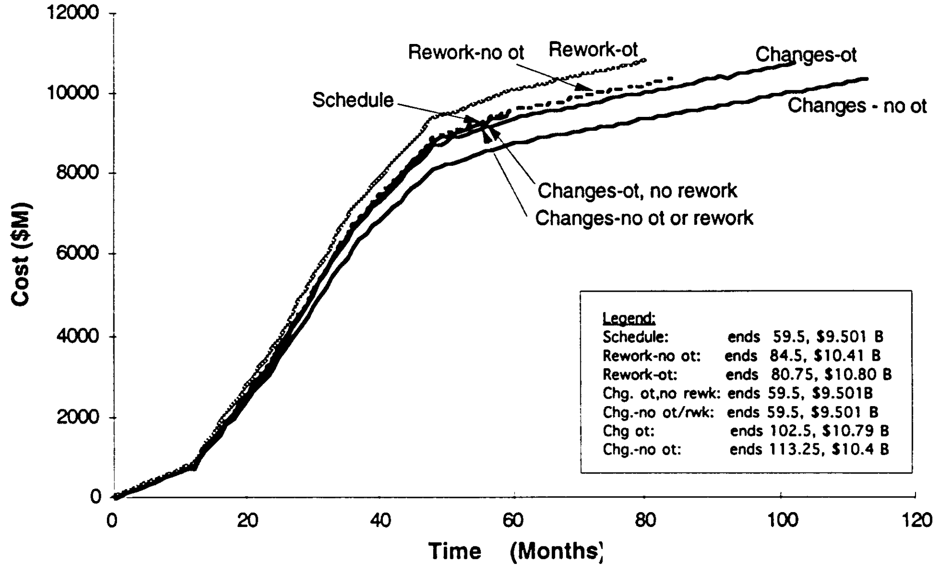


Figure 3.16 Total Development Cost versus Time. Funding Profile and Total Time to develop shown in Tables 4.1 and 4.2.

3.7 Summary

The construction of this model of the interaction between the government and industry in the development of a military project began with a policy analysis of the system. The resulting causal loop diagrams describe as simply as possible the important interactions involved in the problem under consideration.

The causal loop diagrams provide the basis for constructing the stock and flow structure which is the basis of the System Dynamic model. The model has been calibrated against actual project data from the F-18 E/F program and the basic scenarios were run and the results listed in Table 3.5.

While the model has adequately simulated an actual project, the variables whose values can be influenced by outside action will be analyzed in the following chapter to investigate their effect on the output, in cost and time, to determine which variables most strongly influence the output.

References

[1] Augustine. Augustine's Laws. p. 109.
[2] Gansler. Affording Defense. p. 104.

CHAPTER 4
SENSITIVITY ANALYSIS

With the model constructed through this research, the user may both track and predict project progress in a variety of situations. However, the issue of improving performance still has not been addressed. The following sensitivity analysis investigates several constant exogenous variables whose values can be influenced by process improvement procedures. By identifying the constants which most strongly impact the output, this analysis will indicate which variables process improvement practices should first target.

Further, the functions of the model will be investigated for their impact on model results. A function is a non-linear form relating input to output. The functions in this model have been developed through logic, observation, and consultation with experienced System Dynamicists. The functions used in this model are shown in Appendix A.

The sensitivity analysis on these functions will indicate if the function value and amplitude have a strong or weak impact on performance. The resulting ranking of impact strength will indicate which functions should be further investigated for further verification of their shape and amplitude to improve performance and/or accuracy.

The sensitivity analysis has been run against a hypothetical project with the constant values and funding profile shown in Tables 4.1 and 4.2. The following sections evaluate the effects of constant values and functions on the model outputs of Time to Complete Development and Actual Product Cost. Each variable or function has been evaluated against a baseline scenario—the Changes-OT run from Table 3.5—and the initial contract schedule—the Schedule run from Table 3.5. Performance improvements are measured against the baseline—the Changes-OT run. The profile results from this run are shown in Table 4.3.

Table 4.1 Variable Input Values for Hypothetical Project

Variable	Value
Initially Expected Project Cost	$10 B
Initial Work	630,000 person hours
time to do initially scheduled work	72 months

Table 4.2 Funding Profile Input for Hypothetical Project

Year	Funding ($M)	Percent of Total
1	800	8%
2	2,700	27%
3	3,300	33%
4	2,100	21%
5	700	7%
6	400	4%
Total	10,000	100%

Table 4.3 Funding and Actual Progress Profile Output for Baseline.

Year	Actual Funding Profile	Percent of Actual Funding*	Percent of Project Completed (Cumulative)**	Work Done (person-hours per year)
1	799	7.3%	6.5%	51,288
2	2,647.8	24.5%	28.5%	172,421
3	3,321.6	30.6%	56.3%	217,925
4	2,050.3	18.9%	74.4%	146,959
5	683.8	6.2%	80.6%	55,316
6	391.7	3.5%	84.1%	30,250
7	392.8	3.5%	88.5%	33,431
8	394.2	3.6%	92.8%	34,476
9	213.8	1.9%	95%	18,341
Total	10,795	100%	95%	760,407

* Actual Funding is the funding value at 95% completion.

** measured as Work Done Right divided by Work to Do + Work Done Right.

A project is considered to be complete when 95% of the Work to Do has been completed and when the Work Done Right exceeds 95% of the Initial Work. Recall that this model contains numerous complex feedback loops. This level of complexity causes the output to be a non-linear function of the inputs. Also remember that the function profile in Table 4.3 shows that a majority of the project is completed before the schedule completion date. The project is nearly 90% complete by the end of year seven, but does not reach 95% completion until the middle of year 9. This explains the modeled schedule completion at 59.5 months and $9.501B from Figure 3.14.

The ranges of constant values selected were chosen to demonstrate model robustness as well as sensitivity to input variations. By modeling situations outside of the proposed model use (i.e. Productivity of 86—half of normal—or Percent Over Budget Allowance of 100%—200 times normal) this analysis show the model to be applicable not only to the current environment, but dynamic enough to adapt to future changing environments.

Table 4.4 Constants and Functions for Sensitivity Analysis.

Constants	Values	Functions*
Changes per Dollar	low 15,000 baseline 30,000 high 45,000	Budget Pressure on Funding Change
Normal Productivity	low 86 baseline 172 high 344	Budget Pressure
Normal Quality of Work	low 0.2 baseline 0.8 high 0.9	Complexity
Normal Quality of Rework	low 0.2 medium 0.8 baseline 0.9 high 1	Effect of Fatigue on Productivity
Priority	low 0.5 baseline 1 medium 2 high 3	Effect of Fatigue on Quality
Percent Over Budget Allowance	low 0 baseline 0.05 medium 0.5 high 1	Effect of Funding on Workforce
Percent Work Changed Due to Funding Change	low 0 baseline 0.25 medium 0.5 high 1	Effect of Schedule Pressure on Productivity
Speed of Assigning Work	low 1 baseline 3 high 5	Effect of Progress on Workforce
Speed of Reworking	low 1 baseline 2 high 5	Effect of Schedule Pressure on Quality
		Effect of Schedule Pressure on Funding Change
		Schedule Pressure

* See Appendix A for function graphs.

4.1 Constants

The following section will evaluate the effects of constant exogenous variables on the model output. In the following tables, a value less than

100% indicates performance below the baseline or the schedule (80% means the value is 80% of the baseline or schedule). A value greater than 100% indicates performance able the baseline or schedule (125% means the value is 125% of the baseline or schedule).

4.1.1 Changes Per Dollar

Changes per Dollar determines the amount of person-hours of work added to the project due to funding decrease imposed changes. Figure 4.1 shows the accumulation of funds throughout the product development cycle for each of three cases: the "baseline" case with 1 person-hour of work per $30,000 decrease, the "low" case—1 person-hour per $15,000, and the "high" case—1 person-hour per $45,000. Changes are calculated by

$$\frac{\textit{changing funding} * \textit{complexity fn}(\textit{percent changing funding})}{\textit{Changes per Dollar}} \qquad \text{Equation 4.1}$$

Therefore, when Changes per Dollar increases, Work to Do decreases. The baseline value for this variable was chosen through iterative simulation during model calibration. The range of values chosen shows - 50% and + 150% of baseline.

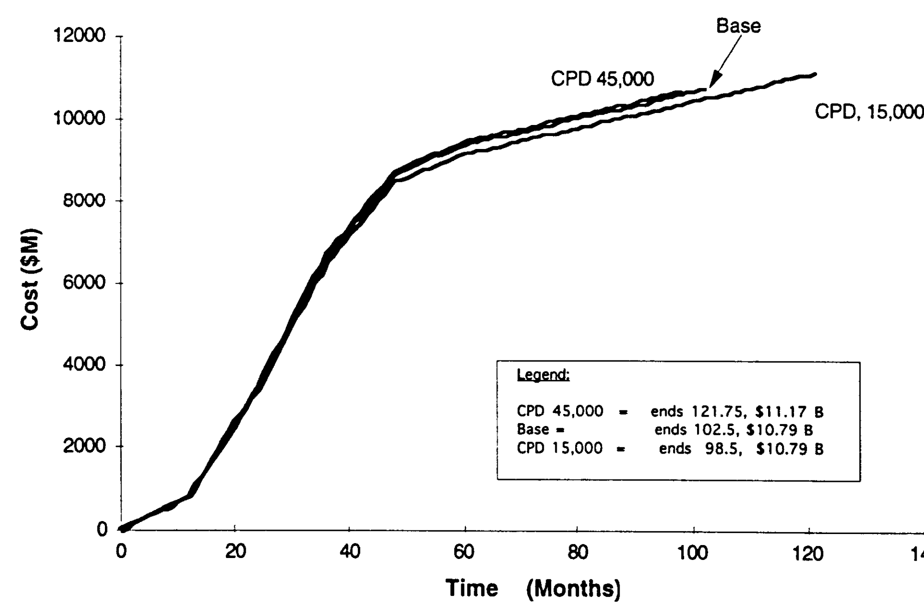


Figure 4.1 Actual Product Cost vs. Time for Changes Per Dollar.

Table 4.5 Changes per Dollar Sensitivity

Case	Completion Time (Months)	Completion Cost ($ B)	% Time		% Cost		Work Done
			vs. baseline	vs. schedule	vs. baseline	vs. schedule	
low — 15,000	121.75	11.17	118.8%	204.6%	103.5%	117.6%	803,493
Baseline— 30,000	102.5	10.79	100%	172.3%	100%	113.6%	760,407
high— 45,000	98.5	10.7	96.1%	165.5%	99.2%	112.6%	750,248

The model development time has a strong sensitivity to Changes per Dollar. The model development cost has a smaller sensitivity to Changes per Dollar. This analysis also shows there is no trade-off between cost and schedule associated with this variable. This means a decrease in time correlates to a decrease in cost and conversely, an increase in time correlates to an increase in cost. This behavior shows a clear path to performance improvement: increasing Changes per Dollar decreases project completion time and cost.

Increased Changes per Dollar indicates design flexibility and contractor responsiveness to change.

4.1.2 Normal Productivity

Productivity is a measure of how much work is actually done per person-hour. Normal productivity is 172 person hours of work completed per month (172 working hours—40 hours per week times 4.3 weeks per month). Productivity can be increased or decreased by the effects of schedule pressure and fatigue, as described in Section 3.4.5. The effect of changes in this variable on project time and cost are shown in Figure 4.2 and Table 4.6.

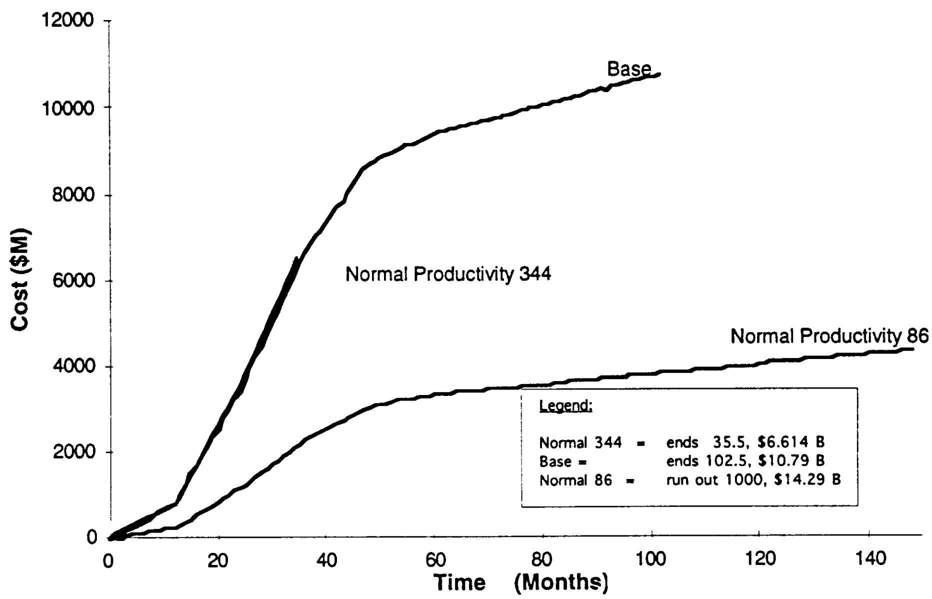


Figure 4.2 Actual Product Cost vs. Time for Normal Productivity.

Table 4.6 Normal Productivity Sensitivity.

Case	Completion Time (Months)	Completion Cost ($ B)	% Time		% Cost		Work Done
			vs. baseline	vs. schedule	vs. baseline	vs. schedule	
low —86*	1000	14.29	-	-	-	-	716,013
Baseline—172	102.5	10.79	100%	172.3%	100%	113.6%	760,407
high—344	35.5	6.614	34.6%	59.7%	61.3%	69.6%	735,532

* Simulation ended at 1000 without project completion.

The model is very sensitive to Normal Productivity both in schedule and cost. As with Changes per Dollar, Normal Productivity has no cost-schedule trade-off for improving performance. Therefore, increasing Normal Productivity will decrease both development cost and time.

Increased productivity results from supplying the workforce with improved tools and processes, allowing work to be completed at a faster rate.

4.1.3 Normal Quality of Work

The quality of work is the percentage of work usually done correctly. This value can be modified by the effects of schedule pressure and fatigue, as described earlier in Section 3.4.7. This variable has been run with three values for sensitivity—a low value of 0.2 (20% quality), a baseline value of 0.8, and a high value at 0.9. Aerospace projects typically have an overall quality (quality of work times quality of rework) of 0.2 to 0.25.[1] This low value is due to the excessive research effort involved in highly complex and technically challenging products. The measure of quality from this research is also based on perfect first time quality.

However, research into several commercial aerospace companies shows quality increasing to the range of 25% to 50%—the normal range for electronic development quality. This model assumes that the project schedule accounts for one rework cycle—an overall quality of 50%. Therefore, the actual quality of the model is 36%: 80% quality of work times 90% quality of rework times 50% quality accounted for in schedule.

The results from this analysis are shown in Figure 4.3 and Table 4.7.

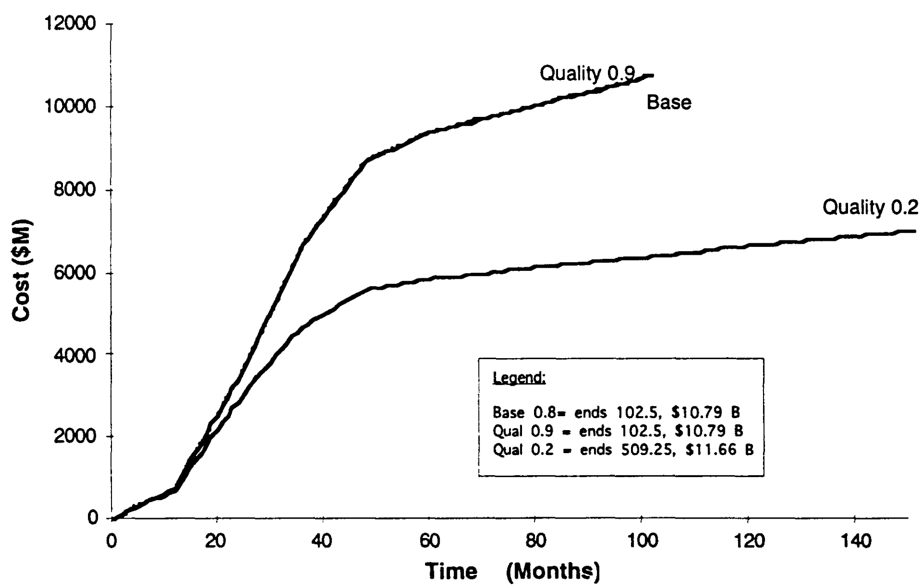


Figure 4.3 Actual Product Cost vs. Time for Normal Quality of Work

Table 4.7 Normal Quality of Work Sensitivity.

Case	Completion Time (Months)	Completion Cost ($ B)	% Time		% Cost		Work Done
			vs. baseline	vs. schedule	vs. baseline	vs. schedule	
low —0.2	529.25	11.16	496.8%	855.9%	108.1%	122.7%	1.293M
Baseline-0.8	102.5	10.79	100%	172.3%	100%	113.6%	760,407
high—0.9	102.5	10.79	100%	172.3%	100%	113.6%	691,302

As expected, Quality of Work has a strong impact on project performance. Due to the non-linear nature of the model, there are diminishing returns on investment as quality continues increasing. In the cases of lower quality, the project falls behind schedule, increasing schedule pressure. An increase in schedule pressure increases productivity, as described in Section 3.4.5. Therefore at lower quality, Work Being Done is greater than at higher quality. This effect accounts for the smaller than expected performance improvement when quality increases. If productivity remained constant throughout the simulation, the time and cost of the project would both be increased dramatically for cases of lower quality.

4.1.4 Normal Quality of Rework

The Quality of Rework is the percentage of rework done correctly. Like the quality of work, this value can also be modified by the effects of schedule pressure and fatigue. This variable has been run with four sensitivity values: 20%, 80%, 90% (baseline), and 100%. The results from this analysis are shown in Figure 4.4 and Table 4.8.

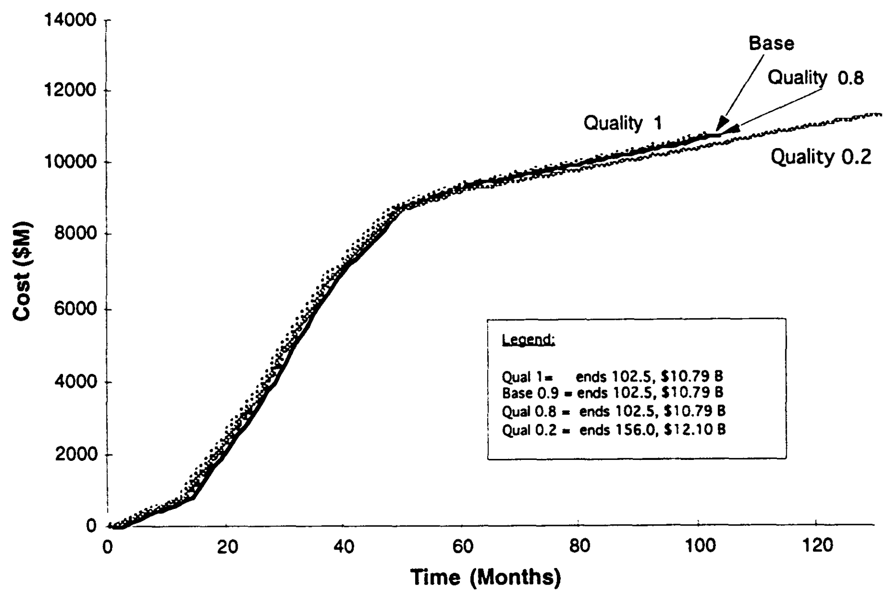


Figure 4.4 Actual Product Cost vs. Time for Normal Quality of Rework

Table 4.8 Normal Quality of Rework Sensitivity.

Case	Completion Time (Months)	Completion Cost ($ B)	% Time		% Cost		Work Done
			vs. baseline	vs. schedule	vs. baseline	vs. schedule	
low—0.2	156	12.10	152.2%	262.2%	112.1%	127.4%	1.136M
Medium—0.8	102.5	10.79	100%	172.3%	100%	113.6%	776,449
Baseline—0.9	102.5	10.79	100%	172.3%	100%	113.6%	760,407
high—1	102.5	10.79	100%	172.3%	100%	113.6%	747,539

The Quality of Rework does not have as strong an impact on performance as does Quality of Work. This result is due to the constant value of Quality of Work in each simulation (at a given work quality the optimal project completion time is constrained to a value correlating to the Quality of Work). This result essentially indicates that the user should attempt to improve quality of work (which gives a larger return on investment) before attempting to improve quality of rework.

4.1.5 Priority

A project's priority measures its relative importance with respect to other projects. A high priority makes more funds available for development. A low priority makes fewer funds available. Figure 4.5 and Table 4.9 show the sensitivity results of the priority variable.

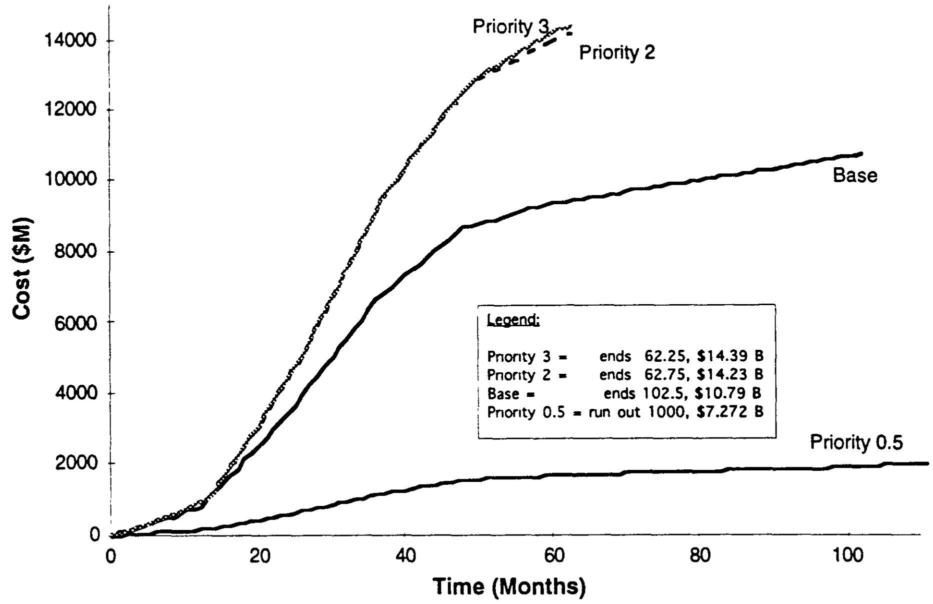


Figure 4.5 Actual Product Cost vs. Time for Priority

Table 4.9 Priority Sensitivity.

Case	Completion Time (Months)	Completion Cost ($ B)	% Time		% Cost		Work Done
			vs. baseline	vs. schedule	vs. baseline	vs. schedule	
Low —0.5*	1000	7.272	-	-	-	-	743,360
Baseline—1	102.5	10.79	100%	172.3%	100%	113.6%	760,407
Medium 2	62.75	14.23	61.2%	105.5%	131.9%	149.5%	760,087
High—3	62.25	14.39	60.7%	104.6%	133.4%	151.5%	764,876

* Simulation ended at 1000 without project completion.

The model is very sensitive to priority changes. However, Priority has a trade-off between cost and development time: an increase in cost decreases development time and a decrease in cost increases time. Therefore, finding the optimal value depends upon which value is more critical, cost or time.

As described earlier the baseline has a priority of one — the project has a priority *equal* to that of all other projects. Therefore, there is no incentive to add funds to the project even when those funds are necessary for the project to meet its schedule. The current political structure of diminishing federal defense outlay means no extra funds are available for discretionary purposes. Therefore, the only way to add funds to the first project is to take them away from another project thus *increasing the first project's priority with respect to the second project's priority.*

Increasing a project's priority requires convincing the Department of Defense and/or Congress that the project is essential to the United States' military mission—more essential than other projects. Therefore, increasing this value is a cooperative process between government and industry.

4.1.6 Percent Over Budget Allowance

The percent over budget allowance sets the amount of additional funding that is allowed to be spent on the project - the project's ceiling cost. This funding makes overtime possible, giving the project funding to meet the schedule.

The baseline value of %5 Over Budget Allowance was derived from consulting with experienced government project officers. A value of 10% is usually the highest possible for a project. However, considering the current trends of decreasing military budgets, this value is also decreasing. The values of 0%, 50%, and 100% were chosen as extremes (although 0% has become increasingly more likely.)

Figure 4.6 and Table 4.10 show the sensitivity results for this variable.

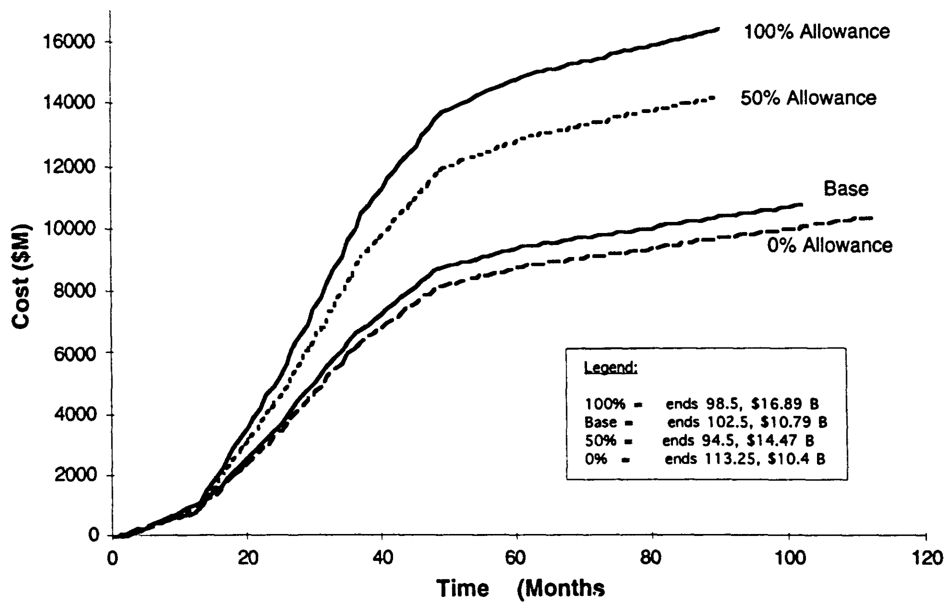


Figure 4.6 Actual Product Cost vs. Time for Percent Over Budget Allowance.

Table 4.10 Percent Over Budget Allowance Sensitivity.

Case	Completion Time (Months)	Completion Cost ($ B)	% Time vs. baseline	% Time vs. schedule	% Cost vs. baseline	% Cost vs. schedule	Work Done
Low —0	113.25	10.4	110.5%	195.3%	96.4%	109.5%	768,076
Baseline—0.05	102.5	10.79	100%	172.3%	100%	113.6%	760,407
Medium 0.5	94.5	14.47	90.2%	158.8%	134.1%	152.3%	779,180
High—1	98.5	16.89	96.1%	177.8%	156.5%	177.8%	820,517

The model is very sensitive to changes in the Over Budget Allowance. These funds represent the project's ceiling. Therefore, the higher the ceiling, the closer the completion date is to the schedule. However, since funding is still dependent upon meeting the initial budget (a dependence that decreases with time but never equals zero), the higher the over budget funds, the more likely funding in future years will be decreased. This feedback is addressed further in Chapter 5.

Over Budget Allowance, like priority, shows a trade-off between cost and time. It is also a value whose optimum (dependent upon the strength of time or budget constraints) must be reached through cooperative efforts between government and industry.

4.1.7 Percent of Work Changed Due to Funding Change

This variable controls the amount of work that is no longer applicable to the project due to funding induced changes. This work is removed from the system, whether it be completed, in need or rework, or yet to be done. The results of these runs are shown in Figure 4.7 and Table 4.11.

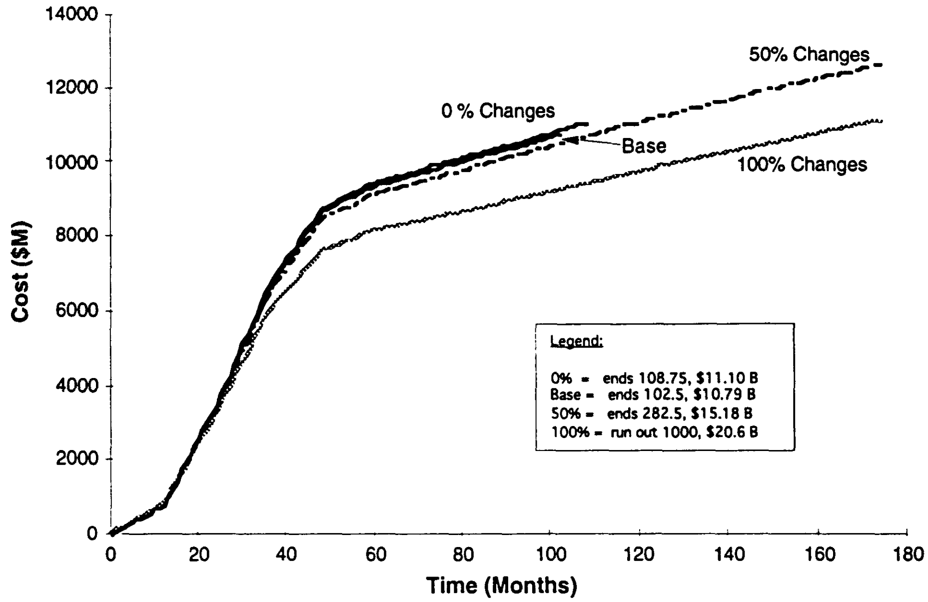


Figure 4.7 Actual Product Cost vs. Time for Percent of Work Changed.

Table 4.11 Percent of Work Changed Sensitivity.

Case	Completion Time (Months)	Completion Cost ($ B)	% Time		% Cost		Work Done
			vs. baseline	vs. schedule	vs. baseline	vs. schedule	
Low —0	108.75	11.10	106.1%	182.8%	102.4%	116.8%	777,886
Baseline—0.05	102.5	10.79	100%	172.3%	100%	113.6%	760,407
Medium 0.5	282.5	15.18	275.6%	474.8%	140.7%	159.8%	772,712
High—1*	1000	20.6	-	-	-	-	720,123

* Simulation ended at 1000 without project completion.

The model is somewhat sensitive to this variable. This analysis also shows the relationship between this variable and the model output to be a positive interaction: an increasing development time yields and increasing development cost. The optimum value lies somewhere between 0% and 50%.

A decreasing Percent of Work Changed correlates to flexibility and responsiveness to change. This decreases work scrapped due to changes in the design.

4.1.8 Speed of Assigning Work

The speed of assigning work is the speed at which work is assigned relative to the speed at which work is done. For example, a value of three means that work is assigned three times faster than it is done. This stage moves the work due to changes to the appropriate areas of responsibility and expertise. While this process goes faster than actually doing the work, it still requires employee time to complete. Figure 4.8 and Table 4.12 show the sensitivity results.

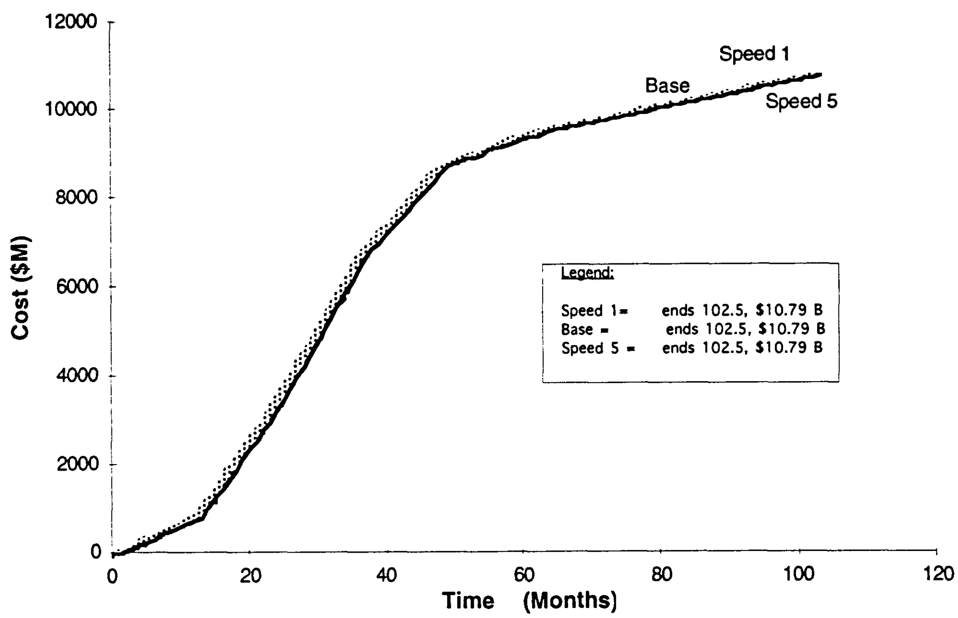


Figure 4.8 Actual Product Cost vs. Time for Speed of Assigning Work.

Table 4.12 Speed of Assigning Work Sensitivity.

Case	Completion Time (Months)	Completion Cost ($ B)	% Time		% Cost		Work Done
			vs. baseline	vs. schedule	vs. baseline	vs. schedule	
Low—1	102.5	10.79	100%	172.3%	100%	113.6%	760,407
Baseline—3	102.5	10.79	100%	172.3%	100%	113.6%	760,407
High—5	102.5	10.79	100%	172.3%	100%	113.6%	760,407

The speed of assigning work has no appreciable impact on project performance. The model does not assign a priority or an importance to work in the system. Therefore, it assumes (incorrectly) that work is independent of other work in the system. Since there is a great deal of work in the stock of Work to Do, increasing or decreasing the speed at which work is added does not impact performance (unless the value approaches or drops below the speed at which work itself is done). A value of Speed of Assigning Work below Speed of Doing Work will cause a net decrease in Work to Do. This causes a bottleneck to occur at Assigning Work, limiting the performance of the project.

4.1.9 Speed of Reworking

The speed of reworking assumes that rework will be done faster than work done the first time. This assumption is based in the belief that employee familiarity with the work and the identification of the problem that caused the work to be redone allows for faster correction. The baseline case has a speed of two (work is redone twice as fast as work is done). Figure 4.9 and Table 4.13 show the sensitivity results.

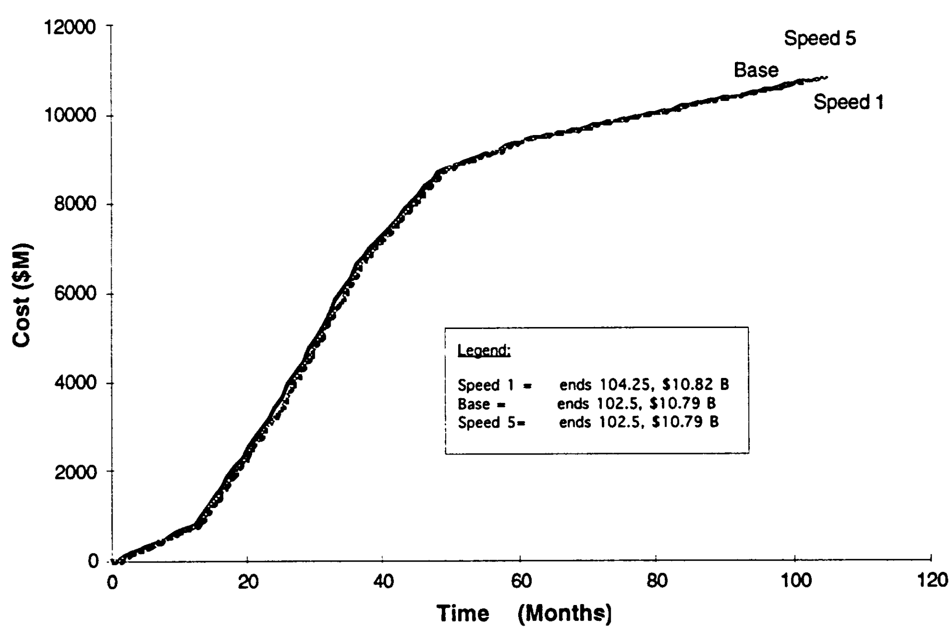


Figure 4.9 Actual Product Cost vs. Time for Speed of Reworking.

Table 4.13 Speed of Reworking Sensitivity.

Case	Completion Time (Months)	Completion Cost ($ B)	% Time		% Cost		Work Done
			vs. baseline	vs. schedule	vs. baseline	vs. schedule	
Low—1	104.25	10.82	101.7%	172.2%	100.2%	117.7%	752,074
Baseline—2	102.5	10.79	100%	172.3%	100%	113.6%	760,407
High—5	102.5	10.79	100%	172.3%	100%	113.6%	760,372

This constant has no appreciable impact on project performance. The reasons for these results are similar to those explained in Section 4.1.8 for Speed of Assigning Work.

4.2 Functions

After analyzing the effects of constants on project performance, the effects of the functions on the model output were investigated. The function sensitivity is measured against the same standard as the variables: the initial schedule and the baseline. Recall that the shape of the model functions and their values were derived from logical analysis, observation, and consultation with experienced System Dynamics modelers. Therefore, the results of this analysis will indicate the functions whose changes in amplitude impact performance. These functions should be further investigated to validate function shape and value in an attempt to improve model accuracy and/or performance.

As in Section 4.1, the sensitivity analysis results are compared to the baseline data. The following analysis compares simulation results from three different functions: the baseline function, the inflated value function (the same function shape but with higher values), and the lower value function (the same function shape but with lower values.). These runs are referred to as IVF and LVF respectively. The actual function graphs can be found in Appendix A.

4.2.1 Budget Pressure on Funding Change

This function takes an input of budget pressure (either current budget pressure or initial) and outputs a value between 0.32 and 1. As discussed in Chapter 3, the low value of 0.32 was derived from research of several projects funding flows: F-22, A-12, C-17, and F-18 E/F. This research showed when project funding was cut, it either decreased between zero and 60%, or it dropped to zero. Therefore, the Normal Times Effects lower limit was 40% (100% - 60%). In a constant priority project, only the Effect of Schedule Pressure and the Effect of Budget Pressure can decrease funding. Since the Normal Times Effects variable is the product of its inputs, the two inputs which change over time were constrained by a lower limit of 0.64— the square root of 0.4.

However, both the Effect of Schedule Pressure and the Effect of Budget Pressure are sums of their two inputs, one dependent upon the initial schedule and one dependent upon the current schedule. This caused the lower limit of the functions—both Schedule Pressure and Budget Pressure— to be constrained to half of the sum, or 0.32.

When the budget pressure is high (the project is far behind schedule), the function output is near 0.32. When the budget pressure is low (the project is near its schedule) the function output is near one. The output of this function is ultimately fed into the normal times effects on funding change. This function causes the approved funding to decrease when the project is over budget in an attempt to bring the expense down. Figure 4.10 and Table 4.14 show the output of this case.

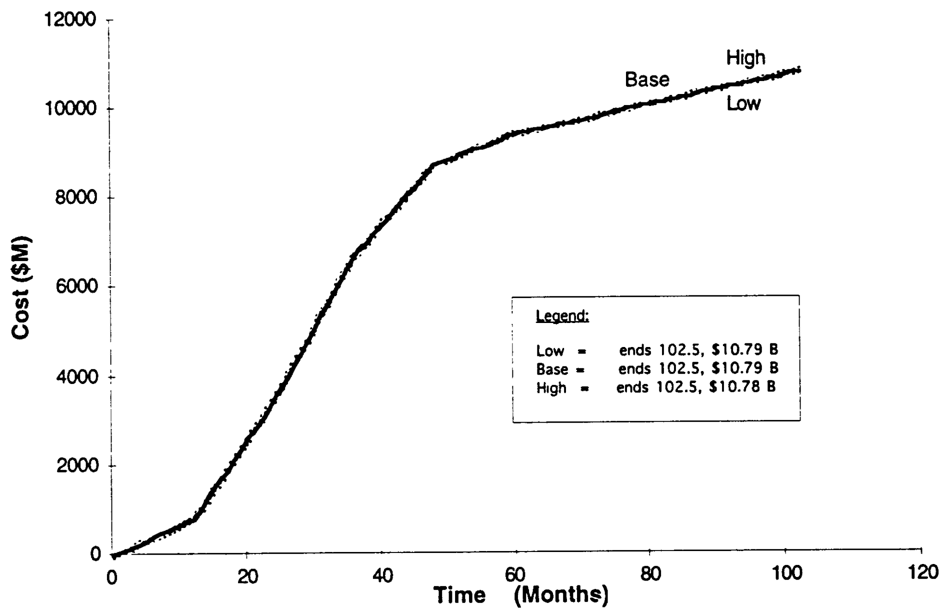


Figure 4.10 Actual Product Cost vs. Time for Budget Pressure on Funding Change.

Table 4.14 Budget Pressure on Funding Change Sensitivity.

Case	Completion Time (Months)	Completion Cost ($ B)	% Time		% Cost		Work Done
			vs. baseline	vs. schedule	vs. baseline	vs. schedule	
Low	102.5	10.6	100%	172.3%	98.2%	113.5%	760,442
Baseline	102.5	10.79	100%	172.3%	100%	113.6%	760,407
High	102.5	10.79	100%	172.3%	100%	113.6%	759,805

Changes in this function has no distinguishable impact on project performance. The model is highly constrained by funding—the company can only spend it's allocation plus ceiling on development. This constraint keeps the company from going over the current budget (current budget = initial allocation plus over budget allowance). Therefore, only extreme cases allow the costs to exceed the initial budget by enough margin to move further along this function. Since the base simulation does not exceed the budget by a large enough value early enough in the project, the results of changing this function do not seem to impact performance. Therefore, this function is not a priority for investigation and validation.

4.2.2 Budget Pressure

This function controls the impact of current budget pressure and initial budget pressure on funding change approval. As time advances, the impact of meeting the initial budget decreases because funding changes were approved by the government. Likewise as time advances, the impact of meeting the current budget increases. Figure 4.11 and Table 4.15 detail these results.

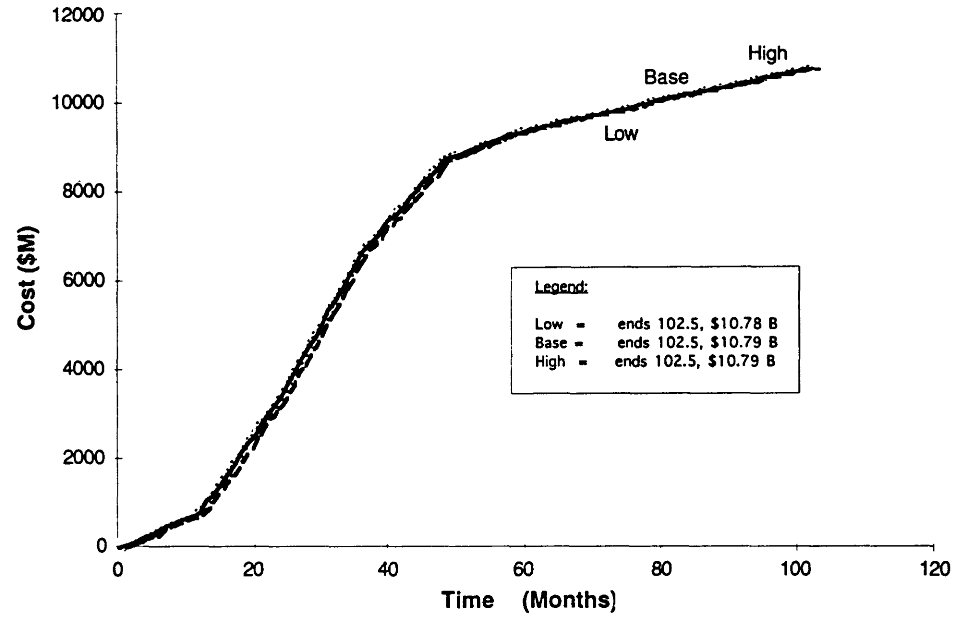


Figure 4.11 Actual Product Cost vs. Time for Budget Pressure.

Table 4.15 Budget Pressure Sensitivity.

Case	Completion Time (Months)	Completion Cost ($ B)	% Time		% Cost		Work Done
			vs. baseline	vs. schedule	vs. baseline	vs. schedule	
Low	102.5	10.78	100%	172.3%	99.9%	111.6%	759,852
Baseline	102.5	10.79	100%	172.3%	100%	113.6%	760,407
High	102.5	10.79	100%	172.3%	100%	113.6%	760,210

Changes in this function have no appreciable impact on project performance. As described earlier, the model is highly cost constrained. Therefore, the gap between the initial budget, the current budget and the actual cost remain small for most of the simulation, minimizing the impact of variations in this function on performance.

4.2.3 Complexity

The Complexity Function converts changing funding to person-hours of work added to the system. When funding decreases are high, the additional work is high. When funding decreases are low, additional work is low. When funding is increased, the additional work added to the system is zero. These results are shown in Figure 4.12 and Table 4.16.

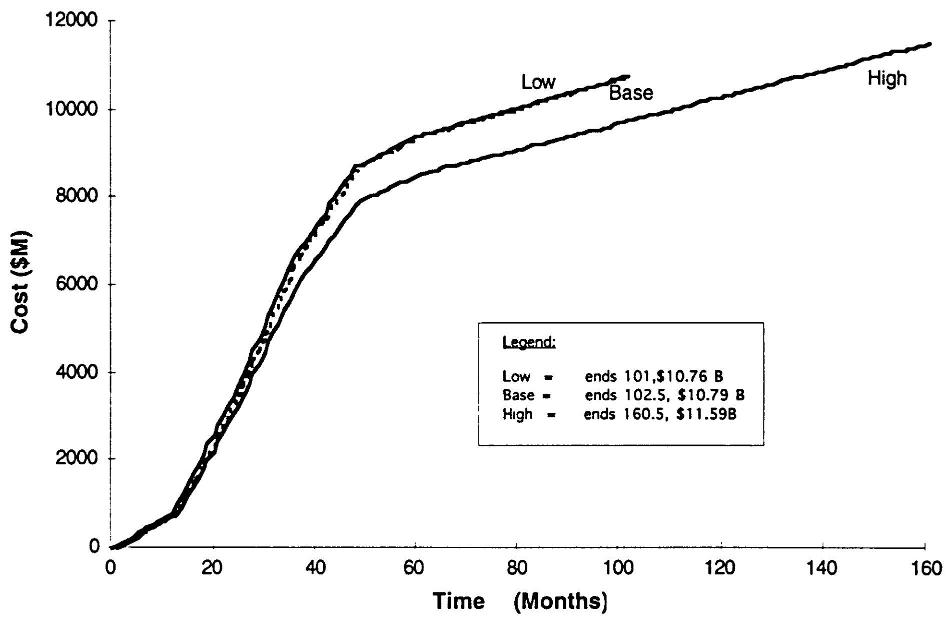


Figure 4.12 Actual Product Cost vs. Time for Complexity.

Table 4.16 Complexity Sensitivity.

Case	Completion Time (Months)	Completion Cost ($ B)	% Time vs. baseline	% Time vs. schedule	% Cost vs. baseline	% Cost vs. schedule	Work Done
Low	101	10.76	98.5%	169.8%	99.7%	113.3%	756,627
Baseline	102.5	10.79	100%	172.3%	100%	113.6%	760,407
High	160.5	11.59	156.6%	269.7%	107.4%	122%	867,878

Changes in this function have a very strong impact on project performance because this function controls the percentage of work added to the system. The LVF decreases the amount of work added to the system and the IVF increases work added. Therefore, this function should be further investigated to validate shape and amplitude.

4.2.4 Effect of Fatigue on Productivity

Fatigue accumulates through excessive and/or long duration overtime work. As fatigue increases productivity decreases. Employees are more tired and therefore less able to complete their work in a timely manner. Conversely, when employees are refreshed they are able to accomplish slightly more work than usual—their productivity is slightly higher than normal. Figure 4.13 and Table 4.17 show the sensitivity of project cost and schedule to the effect of fatigue on productivity function.

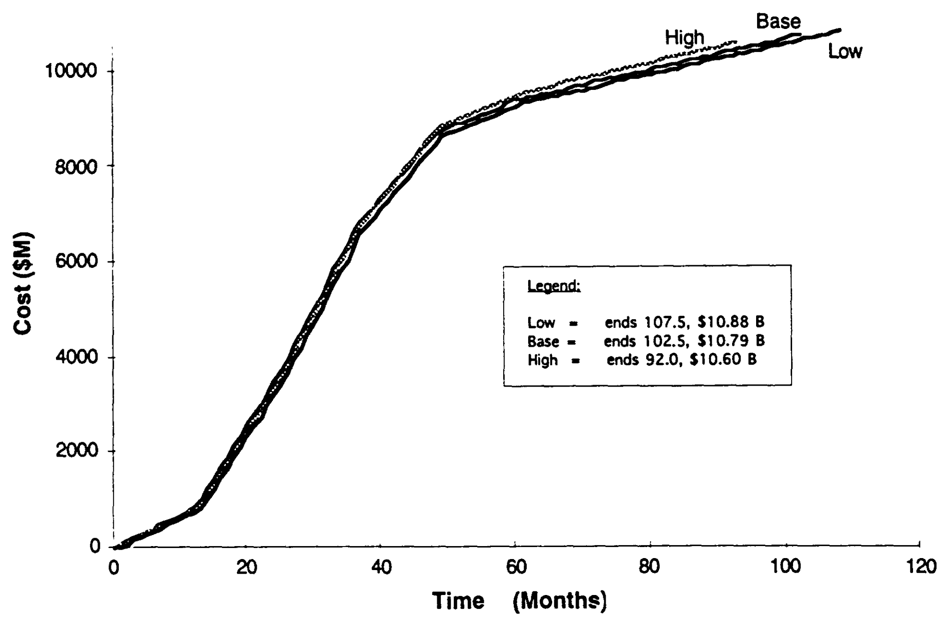


Figure 4.13 Actual Product Cost vs. Time for the Effect of Fatigue on Productivity.

Table 4.17 Effect of Fatigue on Productivity Sensitivity.

Case	Completion Time (Months)	Completion Cost ($ B)	% Time vs. baseline	% Time vs. schedule	% Cost vs. baseline	% Cost vs. schedule	Work Done
Low	107.5	10.88	104.9%	180.7%	100.8%	114.5%	762,914
Baseline	102.5	10.79	100%	172.3%	100%	113.6%	760,407
High	95	10.6	89.8%	154.6%	98.2%	111.6%	754,778

The model is sensitive to changes in this function. While fatigue values in this model are low (cost constraints limit overtime, which in turn limits fatigue), the effect of fatigue on Productivity is high. As shown in Section 4.1.2, the effect of Productivity on performance is high. Therefore, anything sufficiently impacting productivity also impacts overall performance. As a result, this function should be analyzed further for shape and amplitude validation.

4.2.5 Effect of Fatigue on Quality

While fatigue decreases productivity it also decreases quality. As employees tire due to overtime, they become less conscientious and unintentionally make more mistakes. These results are shown in Figure 4.14 and Table 4.18.

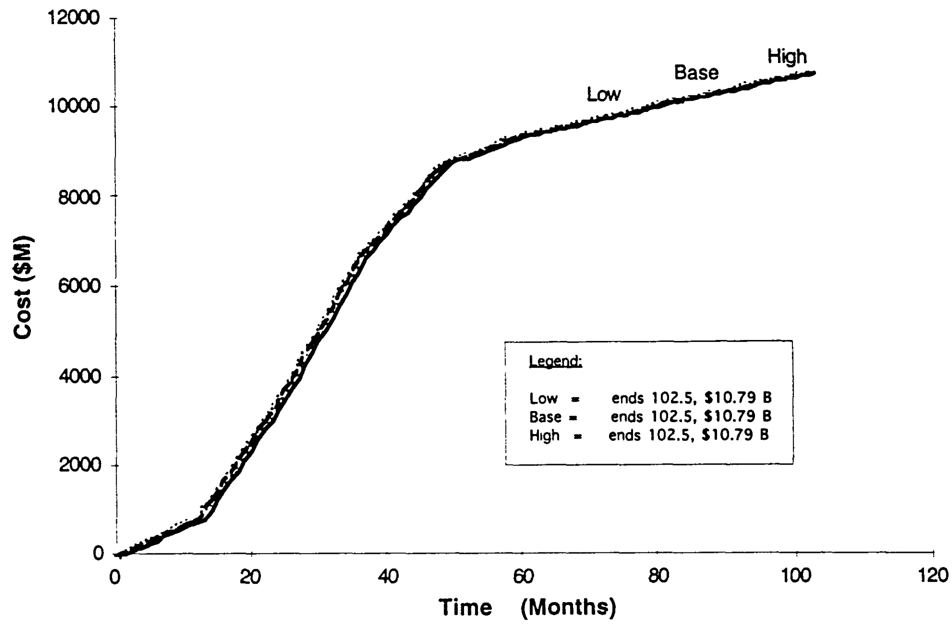


Figure 4.14 Actual Product Cost vs. Time for the Effect of Fatigue on Quality.

Table 4.18 Effect of Fatigue on Quality Sensitivity.

Case	Completion Time (Months)	Completion Cost ($ B)	% Time		% Cost		Work Done
			vs. baseline	vs. schedule	vs. baseline	vs. schedule	
Low	102.5	10.79	100%	172.3%	100%	113.6%	760,411
Baseline	102.5	10.79	100%	172.3%	100%	113.6%	760,407
High	102.5	10.79	100%	172.3%	100%	113.6%	760,407

Due to the high cost constraints on the project, Fatigue is somewhat controlled in this simulation. As described in Section 4.1.3, the return on quality diminishes as quality increases. Since the baseline simulation has a Normal Quality of 0.8, variations from that value have little impact on overall performance. Since Fatigue decreases quality only slightly (less than 0.02) over the duration of the LVF simulation), there is little impact on performance.

4.2.6 *Effect of Funding on Workforce*

This variable increases and decreases the workforce profile based on the available funding. If the funding allocation drops far below expected, this function begins decreasing the workforce. If the funding profile increases, the function will increase the workforce. Figure 4.15 and Table 4.19 show the effect of this function on the model output.

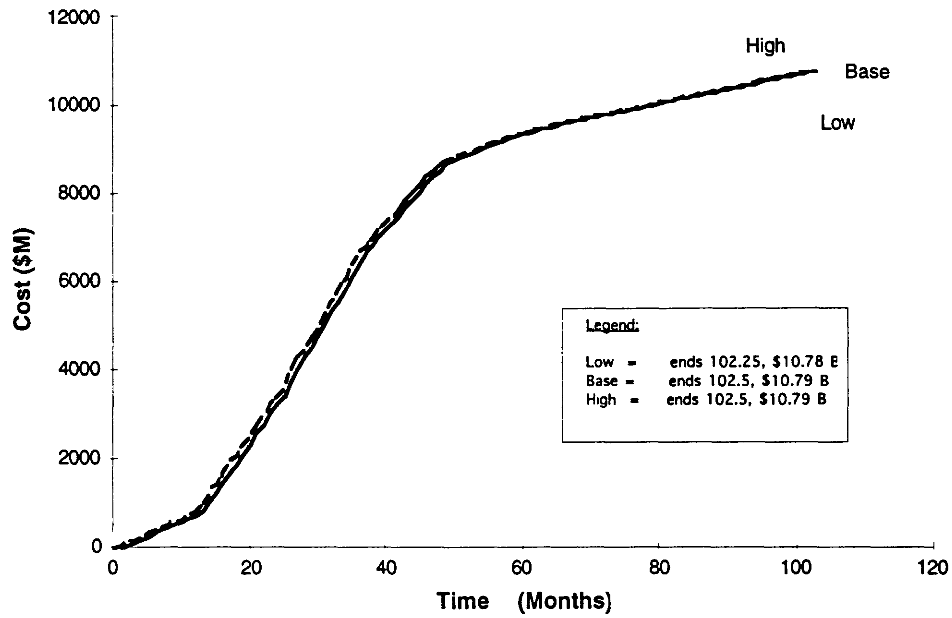


Figure 4.15 Actual Product Cost vs. Time for the Effect of Funding on Workforce.

Table 4.19 Effect of Funding on Workforce Sensitivity.

Case	Completion Time (Months)	Completion Cost ($ B)	% Time		% Cost		Work Done
			vs. baseline	vs. schedule	vs. baseline	vs. schedule	
Low	102.25	10.78	99.9%	171.8%	99.9%	113.5%	759,869
Baseline	102.5	10.79	100%	172.3%	100%	113.6%	760,407
High	102.5	10.79	100%	172.3%	100%	113.6%	760,444

The changes in project performance are small due to changes in this function. This is because the Percent of Changing Funding does not decrease enough to sufficiently influence a change in the workforce through this function, even changing the amplitude of the impact. Therefore, since this function does not sufficiently impact performance, it should be low on the list of functions for investigation and validation.

4.2.7 Effect of Progress on Workforce

When the project is behind schedule, there is an incentive to increase the workforce. More employees will increase the amount of work being done, bringing the project back on schedule. When the project is on schedule, there is no incentive to change the workforce. Figure 4.16 and Table 4.20 show the results.

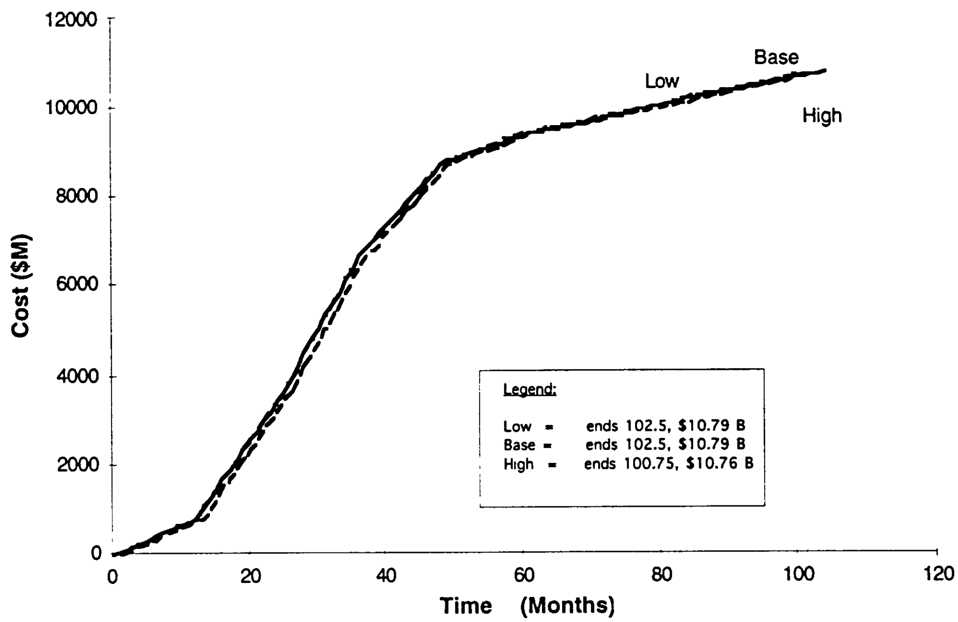


Figure 4.16 Actual Product Cost vs. Time for the Effect of Progress on Workforce.

Table 4.20 Effect of Progress on Workforce Sensitivity.

Case	Completion Time (Months)	Completion Cost ($ B)	% Time		% Cost		Work Done (person-hours)
			vs. baseline	vs. schedule	vs. baseline	vs. schedule	
Low	102.5	10.79	100%	172.3%	100%	113.6%	760,748
Baseline	102.5	10.79	100%	172.3%	100%	113.6%	760,407
High	100.75	10.76	98.3%	169.3%	99.7%	113.3%	759,071

Changes in this function does not have a high impact on schedule performance or project cost. This is because the Percent Perceived Progress does not decrease enough to sufficiently influence a change in the workforce through this function, even changing the amplitude of the impact. The high function cause a small decrease in cost and schedule. However, since this function does not sufficiently impact performance, it should be low on the list of functions for investigation and validation.

4.2.8 Effect of Schedule Pressure on Productivity

High schedule pressure—a project far behind schedule—causes an increase in employee productivity. People work harder to try to get back on schedule. When a project is on schedule there is little pressure to work harder, so productivity is at normal levels. However, when the project is ahead of schedule, people relax a little, decreasing productivity slightly. The effects of this function can be seen in Figure 4.17 and Table 4.21.

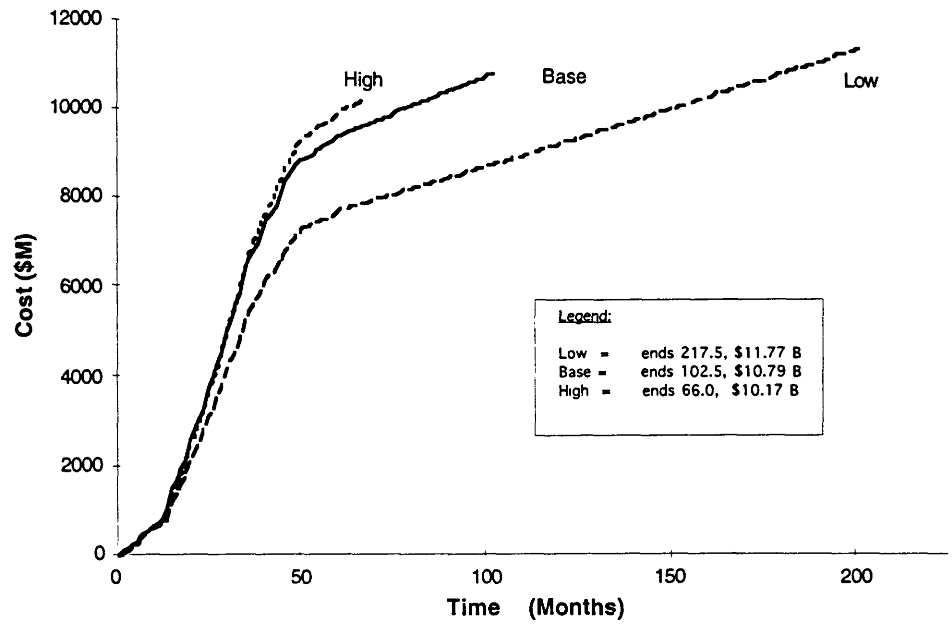


Figure 4.17 Actual Product Cost vs. Time for the Effect of Schedule Pressure on Productivity.

Table 4.21 Effect of Schedule Pressure on Productivity Sensitivity.

Case	Completion Time (Months)	Completion Cost ($ B)	% Time vs. baseline	% Time vs. schedule	% Cost vs. baseline	% Cost vs. schedule	Work Done (person-hours)
Low	217.5	11.77	212.2%	365.5%	109.1%	123.9%	810,567
Baseline	102.5	10.79	100%	172.3%	100%	113.6%	760,407
High	66	10.17	64.4%	110.9%	94.3%	107%	734,779

The changes in this function significantly impact overall project performance. The sensitivity shows that the IVF (high) improves both time and cost. These results show that this function should be investigated to validate its shape and amplitude to improve model performance and/or accuracy.

4.2.9 *Effect of Schedule Pressure on Quality*

When people work faster to try to get back on schedule, the quality of work decreases. Employees are working too fast making more mistakes. When the project is on schedule, the effect of schedule pressure does not change quality. Figure 4.18 and Table 4.22 show these results.

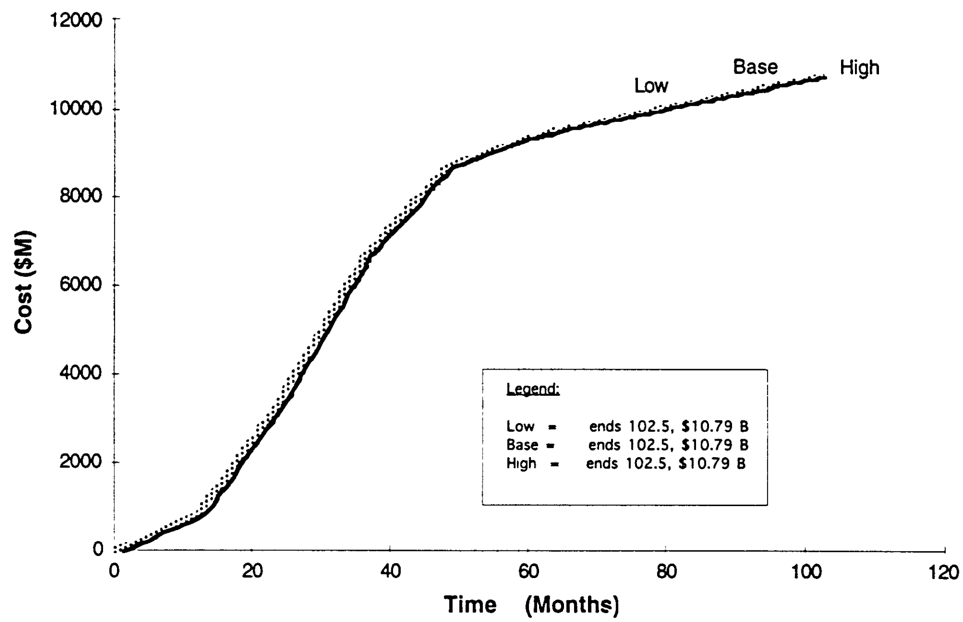


Figure 4.18 Actual Product Cost vs. Time for the Effect of Schedule Pressure on Quality.

Table 4.22 Effect of Schedule Pressure on Quality Sensitivity.

Case	Completion Time (Months)	Completion Cost ($ B)	% Time		% Cost		Work Done (person-hours)
			vs. baseline	vs. schedule	vs. baseline	vs. schedule	
Low	102.5	10.79	100%	172.3%	100%	113.6%	756,806
Baseline	102.5	10.79	100%	172.3%	100%	113.6%	760,407
High	102.5	10.79	100%	172.3%	100%	113.6%	766,604

Variations in the Effect of Schedule Pressure does not measurably impact model performance. Therefore, this function is a lower priority for validation investigation.

4.2.10 Schedule Pressure on Funding Change

A project behind schedule indicates to the government that there may be technical and management issues involved with the project. Therefore, the funding is decreased with the intent of re-evaluating the project and resolving issues before development continues. The effects of this function on project cost and development time can be seen in Figure 4.19 and Table 4.23.

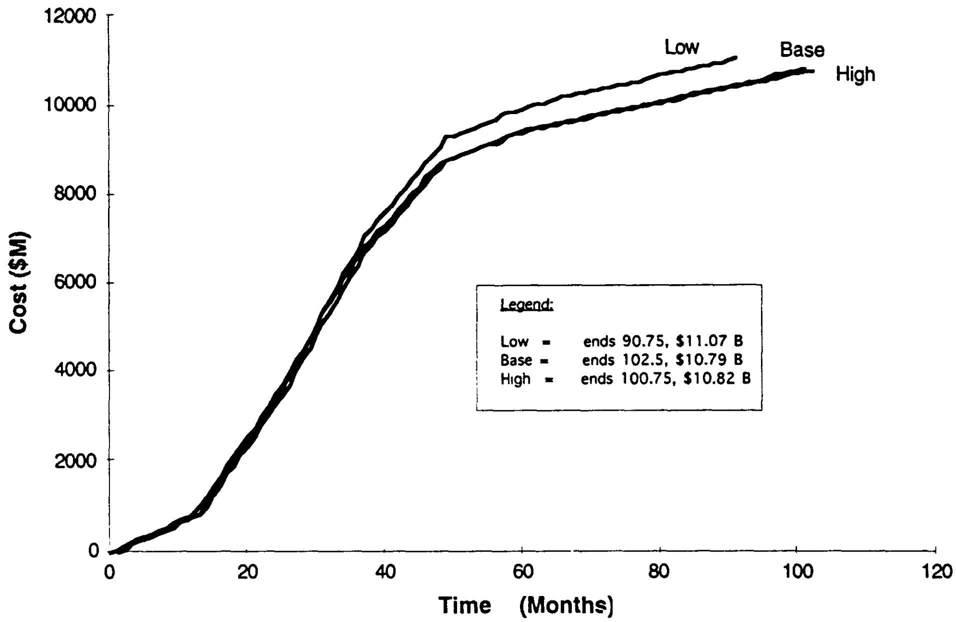


Figure 4.19 Actual Product Cost vs. Time for the Effect of Schedule Pressure on Quality.

Table 4.23 Effect of Schedule Pressure on Funding Change Sensitivity.

Case	Completion Time (Months)	Completion Cost ($ B)	% Time		% Cost		Work Done (person-hours)
			vs. baseline	vs. schedule	vs. baseline	vs. schedule	
Low	90.75	11.07	88.5%	152.5%	102.6%	116.5%	736,888
Baseline	102.5	10.79	100%	172.3%	100%	113.6%	760,407
High	100.75	10.82	98.3%	169.3%	100.3%	113.9%	757,366

The variations in function has an impact on performance. Therefore, this function should be researched to validate its shape and amplitude.

4.2.11 Schedule Pressure

This function controls the impact of current schedule pressure and initial schedule pressure. As time advances, the impact of meeting the initial schedule decreases due to government changes and re-baselined progress. Therefore as time advances the impact of meeting the current schedule increases. Figure 4.20 and Table 4.24 detail these results.

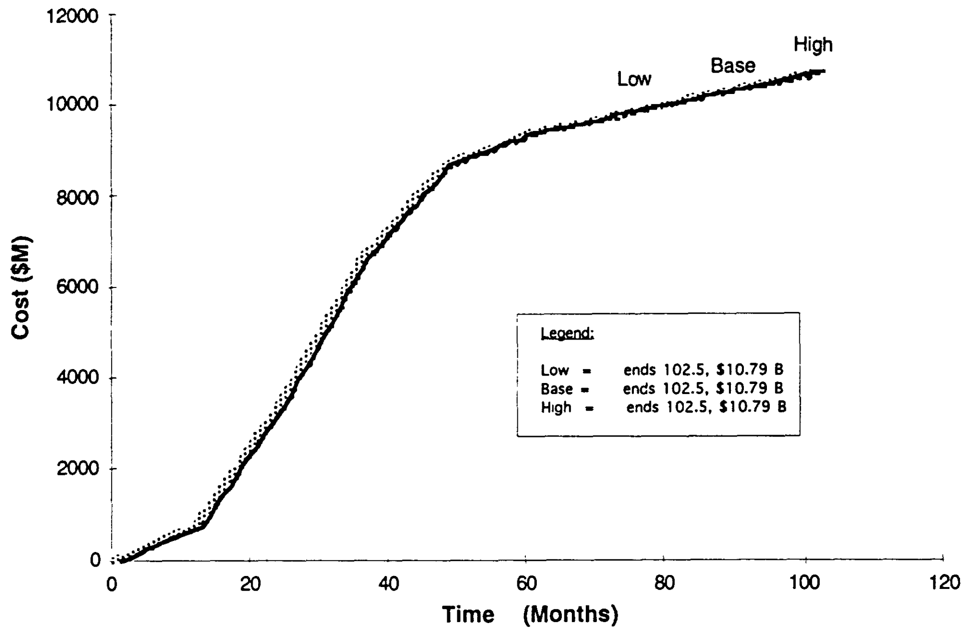


Figure 4.20 Actual Product Cost vs. Time for the Effect of Schedule Pressure on Quality.

Table 4.24 Effect of Schedule Pressure Sensitivity.

Case	Completion Time (Months)	Completion Cost ($ B)	% Time		% Cost		Work Done (person-hours)
			vs. baseline	vs. schedule	vs. baseline	vs. schedule	
Low	102.5	10.8	100%	172.3%	100.1%	113.7%	759,660
Baseline	102.5	10.79	100%	172.3%	100%	113.6%	760,407
High	102.5	10.79	100%	172.3%	100%	113.6%	761,168

Changes in this function do not affect overall project performance. therefore, this function should be low on the list for validation research.

4.3 Summary of Sensitivity Results

This chapter has analyzed the impact of the constants and the functions of this model to determine their impact on project performance. These constants and functions are ranked Tables 4.25, 4.26, 4.27, and 4.28 by their ability to improve project performance. Recall that these functions are complex and highly non-linear. Therefore, the percent improvement/ decrease in performance are measured and ranked against the baseline.

Table 4.25 Constant Value Impact on Schedule Performance.

Constant	"Best" Value*	% Improvement**	% Decrease in Performance***
Normal Productivity	344	65.4%	-
Priority	3	39.3%	-
Percent Over Budget Allowance	0.5	9.8%	10.5%
Changes per Dollar	45,000	3.9%	18.8%
Percent of Work Changed	0.25	0%	-
Normal Quality of Work	0.8, 0.9	0	396.8%
Normal Quality of Rework	0.8, 0.9, 1	0%	52.2%
Speed of Assigning Work	1,3,5	0%	0%
Speed of Reworking	1,2,5	0%	0%

* Value that yields the best results during sensitivity analysis.

** Percent Improvement compared to baseline.

*** Percent Decrease compared to baseline. - indicates data is not available due to model run out.

Table 4.26 Constant Value Impact on Cost Performance.

Constant	"Best" Value*	% Improvement**	% Decrease in Performance***
Normal Productivity	344	38.7%	-
Percent Over Budget Allowance	0	3.6%	56.5%
Changes per Dollar	45,000	0.8%	3.5%
Percent of Work Changed	0.25	0%	40.7%
Priority	1	0%	33.4%
Normal Quality of Rework	0.8,0.9,1	0%	12.1%
Normal Quality of Work	0.8,0.9	0%	8.1%
Speed of Reworking	2 or 5	0%	0.2%
Speed of Assigning Work	3 or 5	0%	0%

* Value that yields the best results during sensitivity analysis.

** Percent Improvement compared to baseline.

*** Percent Decrease compared to baseline. - indicates data is not available due to model run out.

Table 4.27 Function Value Impact on Schedule Performance

Constant	"Best" Value*	% Improvement**	% Decrease in Performance***
Effect of Schedule Pressure on Productivity	High	35.6%	112.2%
Schedule Pressure on Funding Change	Low	11.5%	1.7%
Effect of Fatigue on Productivity	High	10.2%	4.9%
Effect of Progress on Workforce	High	1.7%	0%
Complexity	Low	1.5%	56.6%
Schedule Pressure	High	0.2%	0%
Budget Pressure	Low	0.2%	0%
Effect of Funding on Workforce	Low	0.2%	0%
Budget Pressure on Funding Change	Baseline, Low or High	0%	0%
Effect of Fatigue on Quality	Baseline, Low or High	0%	0%
Effect of Schedule Pressure on Quality	Baseline, Low or High	0%	0%

* Function that yields the best results during sensitivity analysis.

** Percent Improvement compared to baseline.

*** Percent Decrease compared to baseline. - data is not available due to model run out.

Table 4.28 Function Value Impact on Cost Performance

Constant	"Best" Function*	% Improvement**	% Decrease in Performance***
Effect of Schedule Pressure on Productivity	High	5.7%	9.1%
Schedule Pressure	High	3.4%	0.1%
Complexity	Low	0.3%	7.4%
Effect of Fatigue on Productivity	High	1.8%	0.8%
Effect of Progress on Workforce	High	0.3%	0%
Effect of Funding on Workforce	Low	0.1%	0%
Budget Pressure on Funding Change	Low	0.1%	0%
Budget Pressure	Low	0.1%	0%
Schedule Pressure on Funding Change	Baseline	0%	2.6%
Effect of Fatigue on Quality	Low, Baseline, or High	0%	0%
Effect of Schedule Pressure on Quality	Low, Baseline, or High	0%	0%

* Function that yields the best results during sensitivity analysis.

** Percent Improvement compared to baseline.

*** Percent Decrease compared to baseline. - data is not available due to model run out.

Tables 4.27 and 4.28 indicate the ranking of functions where further research may improve the model performance and/or accuracy. Changes in the amplitude of these functions causes significant changes in the model output. Therefore, the model is sensitive to changes in these functions. The most important function in this model to validate is the Effect of Schedule Pressure on Productivity as it causes significant changes in both development time and cost. The order of investigating other functions depends upon the importance of schedule versus cost. If cost improvements are more important—in some cases at the expense of development time—the cost table should be followed. If schedule is more important, the schedule table should be followed.

Tables 4.25 and 4.26 indicate the ranking of constant exogenous variables by both schedule time improvement and cost improvement. The percentages listed in these two tables show improvements and decreases in performance with respect to the baseline. If a project's constant exogenous inputs are higher or lower than the baseline, the percent improvement, and therefore the ranking, will be different.

This sensitivity analysis shows that process improvement practices should begin first with Normal Productivity, as improvements in this variable significantly decrease both cost and development time.

However, most importantly this research has shown that System Dynamics is a modeling approach appropriate to this area (i.e. aerospace and government, both individually and jointly) and that the model generated through this research is capable both or simulating scheduled performance and predicting performance. The additional power of System Dynamics modeling allows the user to change the policy structure of the model (changing priority, changes added, effects on funding change) with minimal effort. This power means the model can be rapidly adapted to new scenarios, an important strength in the aerospace industry's rapidly changing environment.

References

[1] Cooper. The Rework Cycle. p. 182.

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CHAPTER 5
CONCLUSION AND FUTURE RESEARCH

This research has been directed at identifying the major interactions between the government and industry during the development phase of a military project. The increasing complexity of the military procurement system has added to the cost of military projects. Deeper levels of management, added oversight, and excessive scrutiny of expenses in a military project has resulted in a burdensome development system. Military aircraft once developed in three to five years can now require ten or more years of development to achieve designs of comparable complexity—even after normalizing to then-year technological capability.[1]

The output of this research is a dynamic model capable of predicting project timeline behaviors based on a variety of inputs. This model will serve as a tool for project managers—both government System Program managers and contractor project managers—to track a project's progress and evaluate the impact of changing requirements and political actions on project performance. This predictive power will allow the manager to re-baseline schedule progress after funding changes more accurately and in a shorter time. This tool will also give the manager a basis for requesting more funding earlier in the project by predicting cost and schedule growth in future years due to funding decreases in the current year. The capabilities of the model can be further refined by addressing the areas for future research in Section 5.2.

5.1 Review of Results

The System Dynamics model described in this thesis has been built based on an analytical assessment of the policies and government and industry interaction within the military aircraft development system. The model has been calibrated against the actual development history of the F-18 E/F project. The results of this calibration, shown in Figure 3.14, show that this model can effectively represent the development cycle of a military aircraft.

The variables in the calibrated model were then tested to determine the model output sensitivity to changing variable values. This analysis identified the variables that should first be targeted for process improvements. The variable highest on this list is Normal Productivity. Improving this variable decreases both development time and cost. The remaining variables and their relative importance to model output are listed in Tables 4.25, 4.26, 4.27, and 4.28.

5.2 Future Research

As shown in the calibration results, this model has a strong ability to model an actual program. While these results are extremely useful and contribute to the improvement of the design development process, the capabilities of the model can be refined through further research. Most importantly, the robustness of the model should be examined by calibrating the model against a variety of other programs. Specifically, further research in the following areas will refine model detail and improve user-friendliness.

5.2.1 *Workforce*

This model assumes a workforce profile based on the project funding profile. This assumption allows the workforce to increase and decrease based on yearly funding but it does not account for the time required to hire and train new employees for the project. Therefore, their productivity is overestimated. The productivity of new employees increases as they spend less working time learning about the project.

This workforce profile also constrains how project costs are accrued. The project is only charged for the number of person hours worked. Therefore, underutilized employees do not create a cost burden on the system as examined by the model. Most actual projects charge based on the number of employees allocated and not on the number of hours worked. Thus, the model underestimates actual product cost. Further research to determine the relationships between workforce size, project scope, and funding changes will a more realistic workforce analysis of the structure and will allow a more accurate projection of costs.

5.2.2 *Work Added*

Recall that work is added to the system based on the percentage of a funding decrease and an associated smoothing function, shown in Figure 5.1.

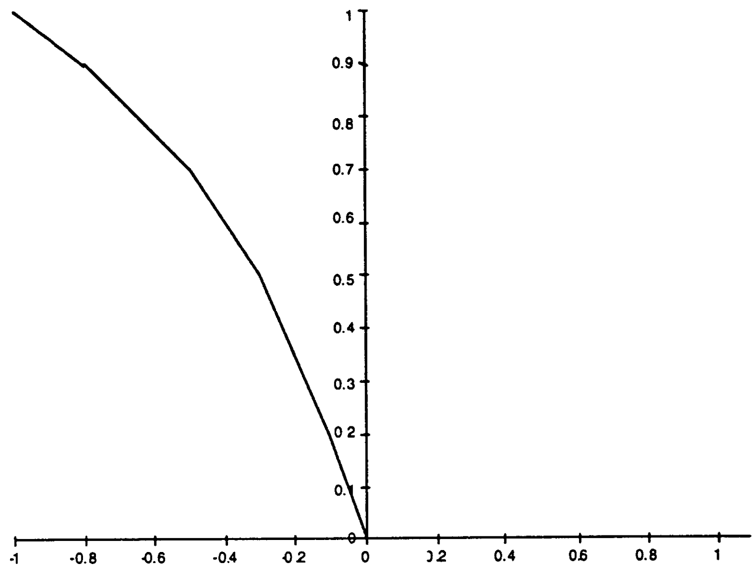

Figure 5.1 Complexity Function. Input along the X axis, output along the Y.

This method of adding work to the system does not account for the importance of the work added. In any real project, much of the work is interdependent, as a solution in one area impacts multiple areas. To account for this, the model increases the number of person-hours of work for large funding changes based on the assumption that large funding changes correlate to complex design changes.

However, this algorithm is only a slightly more accurate representation of the system. Since the interdependence of work has not been modeled, the effects of Speed of Assigning Work and Speed of Reworking are minimized in the simulation. In a system with a large queue of work to be done, the rate of work addition to the system does not impact performance.

Further analysis of this issue will account more accurately for the importance of the Speed of Assigning Work and the Speed of Reworking.

5.2.3 *Flight Simulator*

Finally, this model does not simulate independent exogenous changes that might occur during simulation. For example, if the Priority of the project changes, the model will not incorporate that change unless it was specified prior to simulation.

To account for the interactive nature of defense procurement, this model should incorporate a "flight simulator" approach to military procurement process. The term "flight simulator" was selected specifically to emphasize the interactive nature of a video game or training aircraft flight simulator. Such programs allow the user to make real-time adjustments and reactions to environmental variations. This would allow the user to model increasingly complex possibilities for project performance. By rapidly compiling results at very little cost, such a flight simulator version would amplify the model's intrinsic simulation strengths by providing a more "packaged" user interface for addressing "what-if" scenarios.

5.3 Summary

The result of the research conducted on this project is a dynamic, adaptable model of the government-industry relationship during military development procurement. Recall that in System Dynamics modeling, the characteristics of the system and the output are more important than the actual numbers. Therefore, this model presents two unique contributions to the issue: 1.) the causal loop diagrams constructed during model development provide new insight and understanding of the interactions involved in this process, and 2.) the System Dynamics model developed from this research will provide users a benchmark analysis of the development procurement system and allow rapid simulation of a variety of scenarios to predict the trend of a product's development time and cost. This last contribution could ultimately be a basis for influencing change within the government-industry partnership and provide support for influencing short-term change to improve product development time and cost.

References

[1] Gansler. Affording Defense. p. 8.

APPENDIX A

MODEL DETAILS

A.1 Model Instructions

The following section contains step by step instructions of how to set up and run this model on a potential project or one in process. The process used to generate the hypothetical profile used in Chapters 3 and 4 will be used as a guide.

1. The following data will be necessary:

   contract funding profile (funding per year), total cost, and schedule completion date (Table A.1),

   actual funding profile, dollars per year. If the project is not complete, use the information to date. If the project has not started, continue to the next step. (This data not available for the hypothetical project),

   maximum number of project employees (100)

Table A.1 Funding Profile Input for Hypothetical Project

Year	Funding ($M)	Percent of Total
1	800	8%
2	2,700	27%
3	3,300	33%
4	2,100	21%
5	700	7%
6	400	4%
Total	10,000	100%

2. The funding initial profile must be converted to percentage profile. Simply divide the year's funding by the total expected cost. (Table A.2)
3. The work to do must be calculated. Multiply the percentage funding for the year with the maximum number of employees times twelve months per year times the Normal Productivity and divide by the

maximum percentage funding ((x %*100 people * 172 hours/ month *12 months per year)/33%)

Table A.2 Funding Profile Input for Hypothetical Project

Year	Funding ($M)	Percent of Total	Percent of Employees*	Work to Do (person-hours)
1	800	8%	24.24%	50,036
2	2,700	27%	81.81%	168,873
3	3,300	33%	100%	206,400
4	2,100	21%	63.63%	131,345
5	700	7%	21.21%	43,782
6	400	4%	12.12%	25,018
Total	10,000	100%		625,454

* Percent of Total/Maximum Percent of Total

4. Calibrate against the schedule. Make the following modifications to the model

   Normal Quality W = 1

   Percent Over Budget Allowance = 0

   Making Changes = 0

   Normal Times Effects = 1

   Initial Funds Allocated = Expected Project Cost ($10 Billion)

   actual profile = step function of percentage values in Table A.2 Percent of Total column. Each step occurs at the beginning of the year.

   maximum percentage funding = maximum percentage in Table A.2 Percent of Total column (33%)

   Initial Work = (discussed below)

5. Iterate to find the Initial Work value. The Work to Do calculated in Table A.2 is a starting point for actual Initial Work. Due to the highly integrated nature of the feedback structure and the rounding errors when calculating Work to Do, a poor value for initial work can start the model out of equilibrium. After a few iterations, the value of 630,000 person hours of work was found for the hypothetical project.

6. Reset the model by returning the following variables to their original values

   Normal Quality W

   Percent Over Budget Allowance

Making Changes

Normal Times Effects

7. Change Initial Work to the value generated in Step 5.
8. If there is actual data available, calibrate the model against that by adjusting Changes per Dollar, Complexity Function, and perhaps Quality and Productivity (in that order).
8. Run the model. By changing various variables, as discussed in chapter 4, the model will show the effects of changing scenarios on project performance.

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A.2 Model Graphical Format

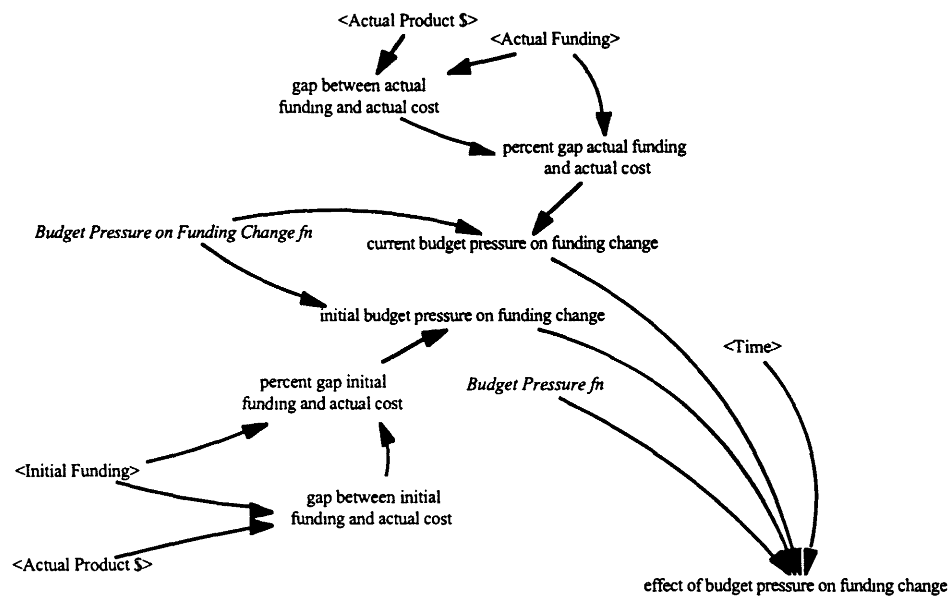

Figure A.1 Effect of Budget Pressure on Funding Change

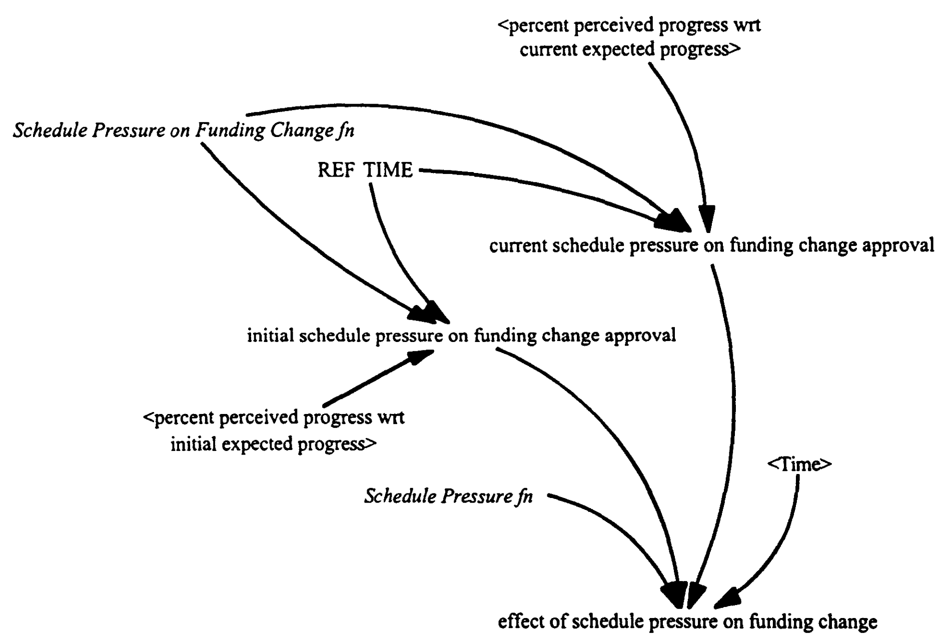

Figure A.2 Effect of Schedule Pressure on Funding Change

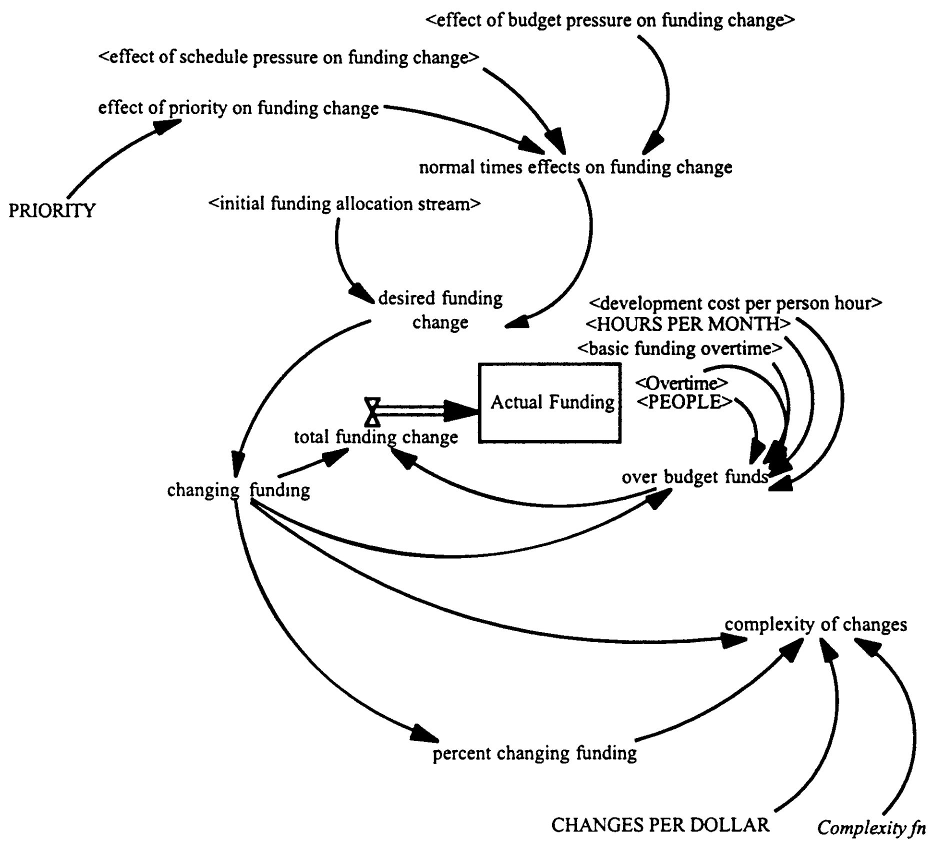

Figure A.3 Government Funding

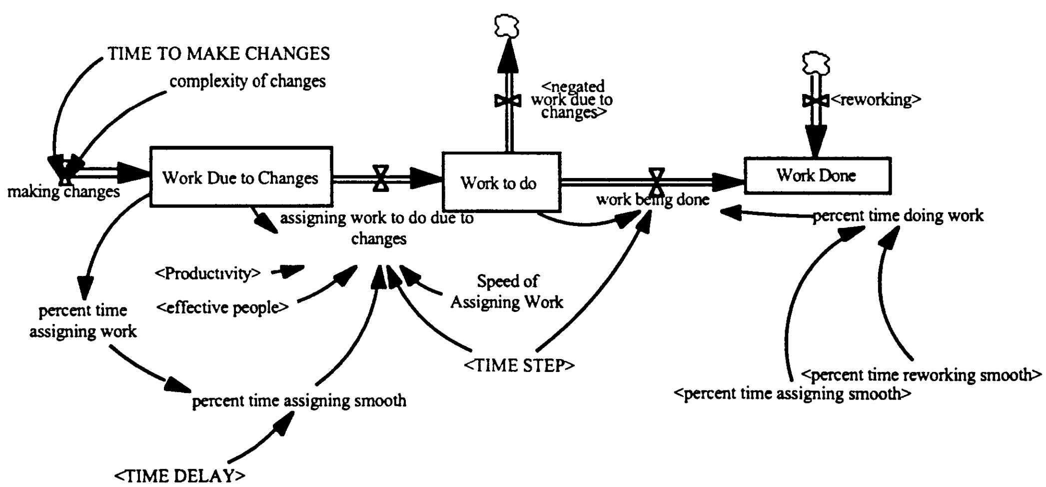

Figure A.4 Corporate Development Process

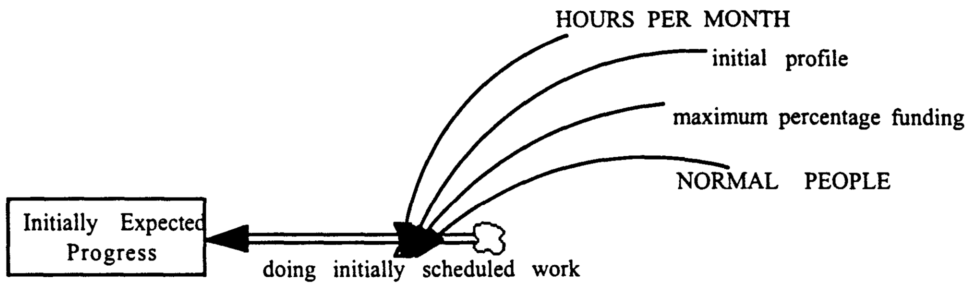

Figure A.5 Initial Schedule Progress

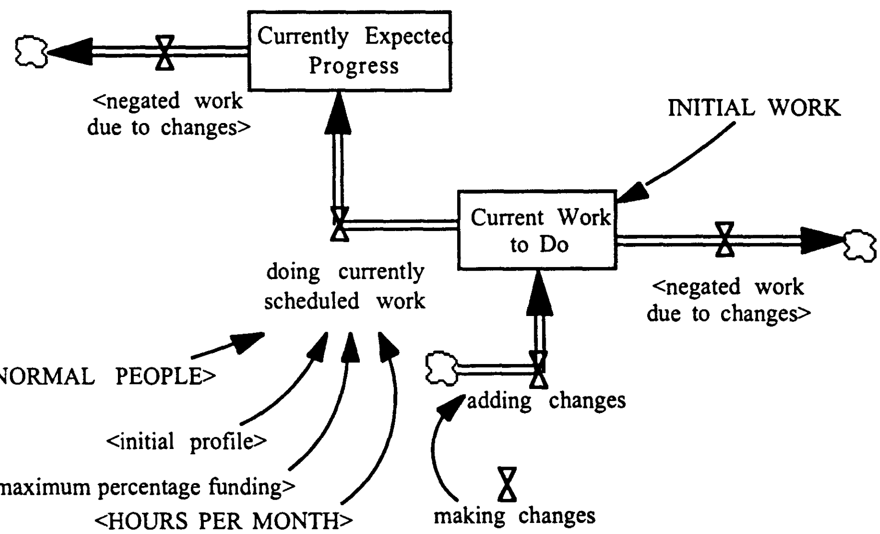

Figure A.6 Current Schedule Progress

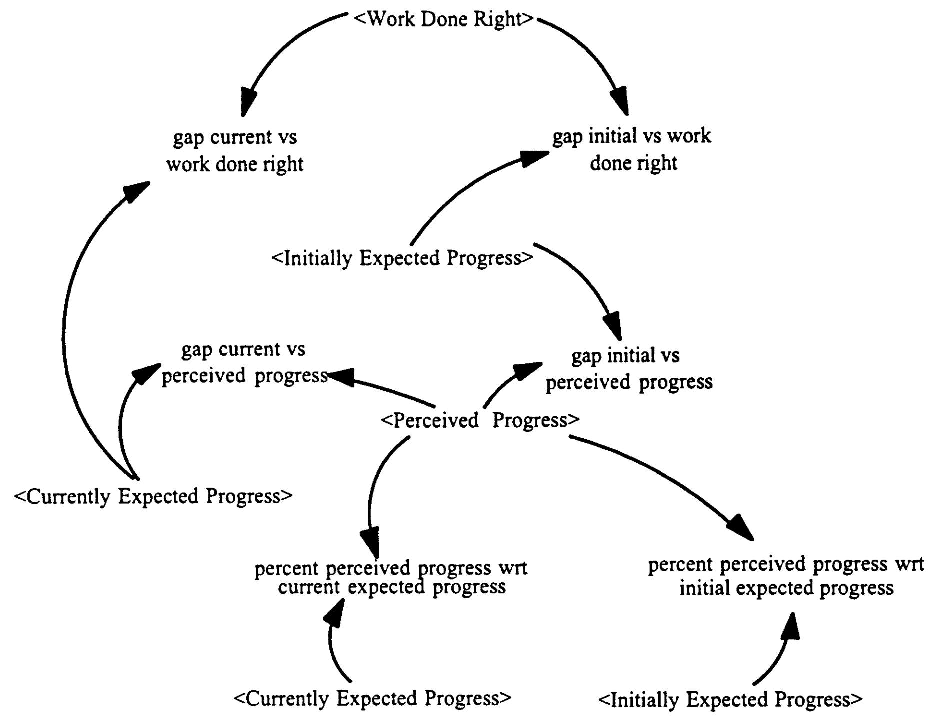

Figure A.7 Progress Calculation

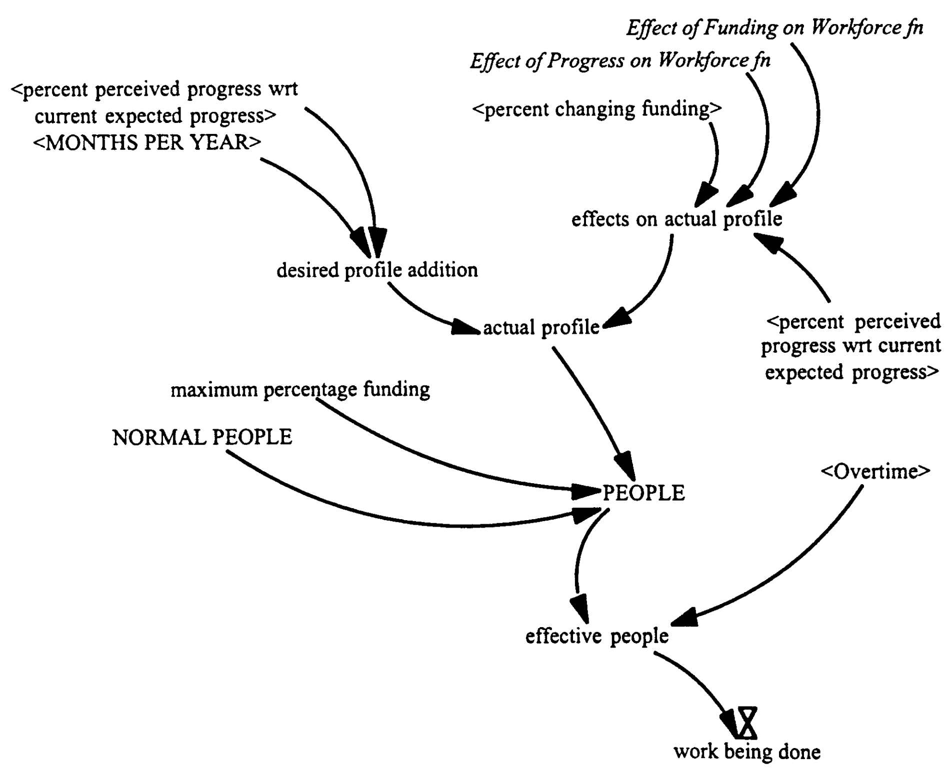

Figure A.8 Workforce

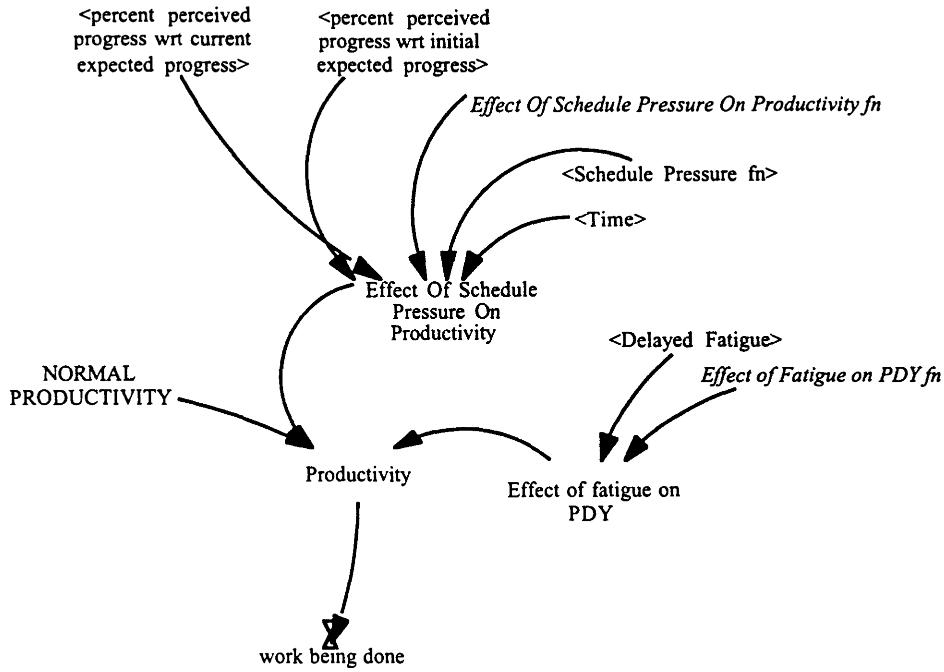

Figure A.9 Productivity

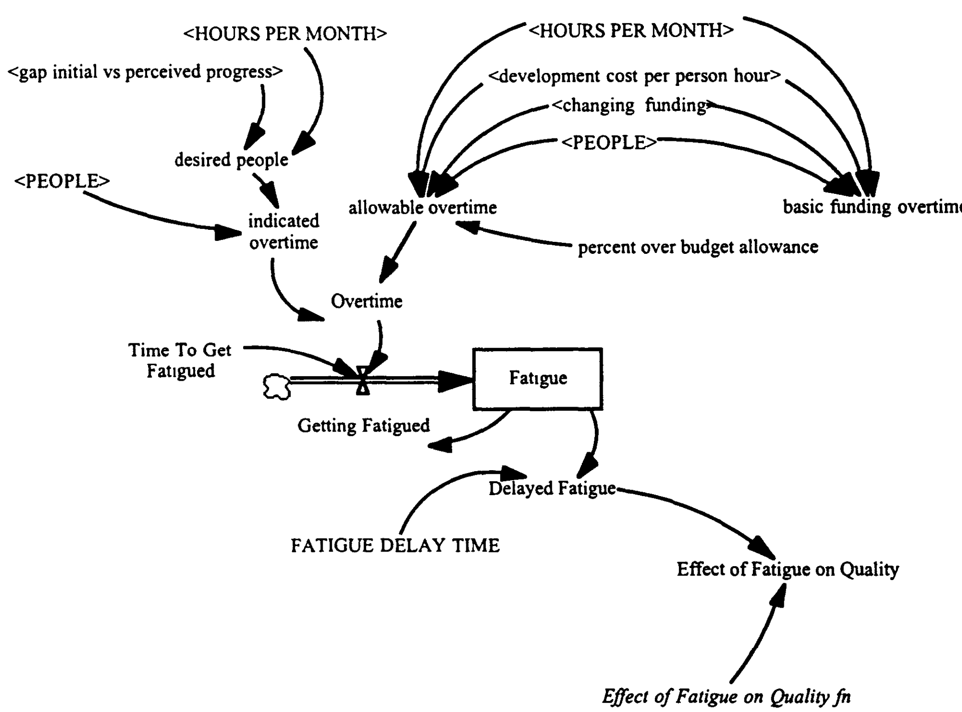

Figure A.10 Fatigue and Overtime

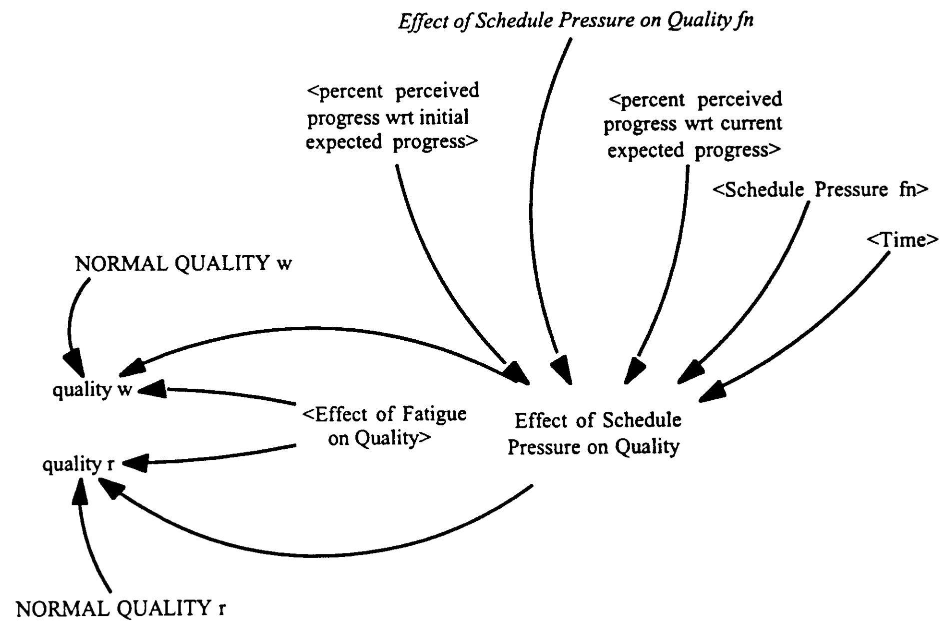

Figure A.11 Quality

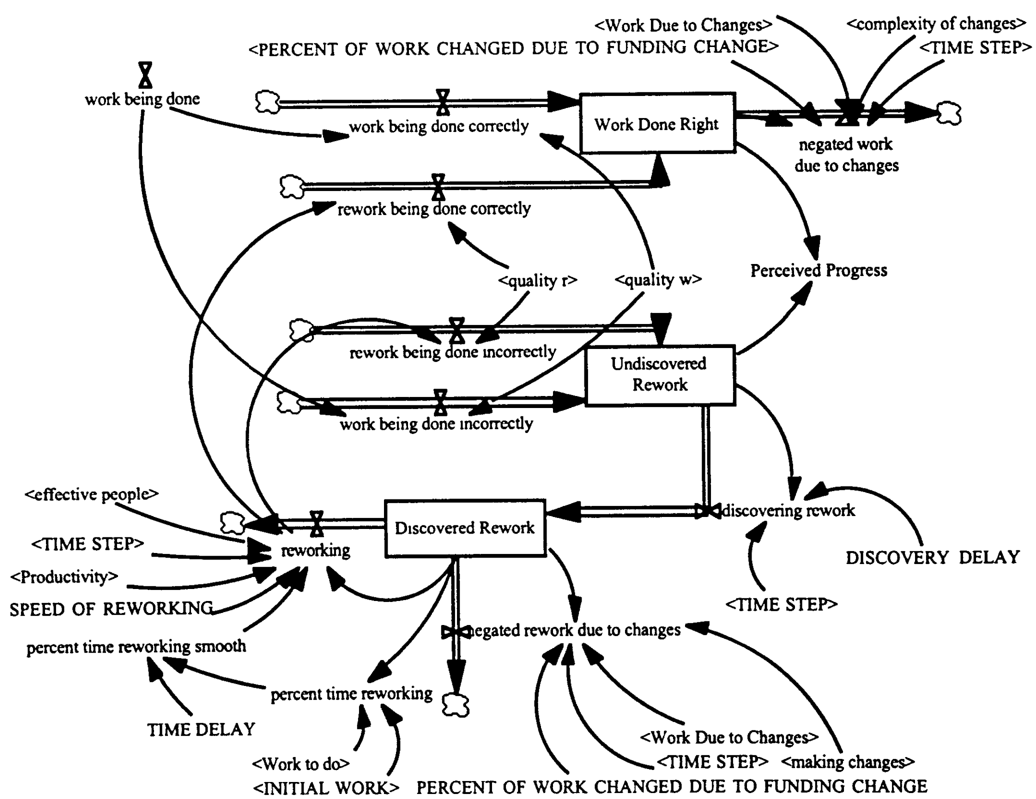

Figure A.12 Rework Cycle

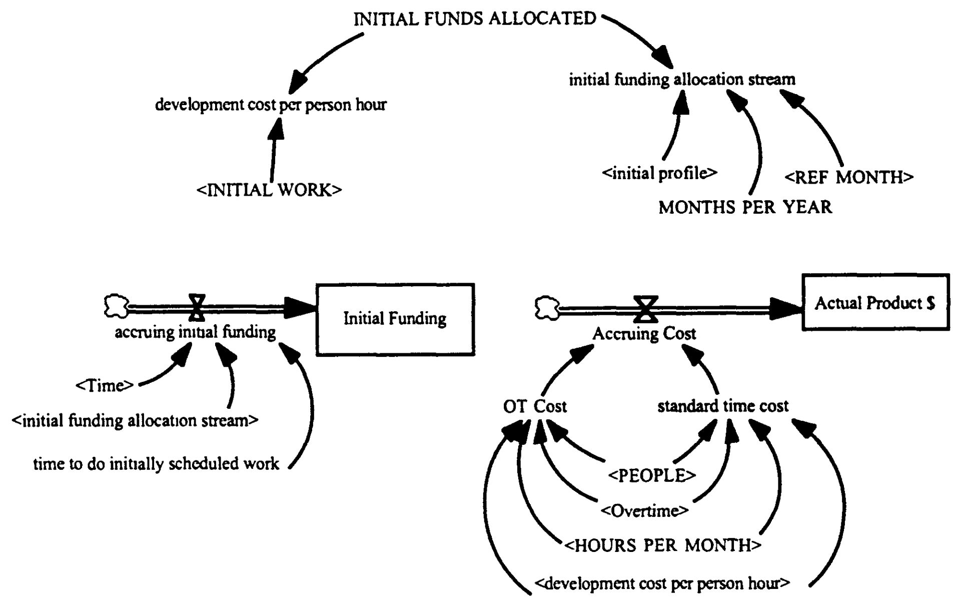

Figure A.13 Financial

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A.3 Model Functions

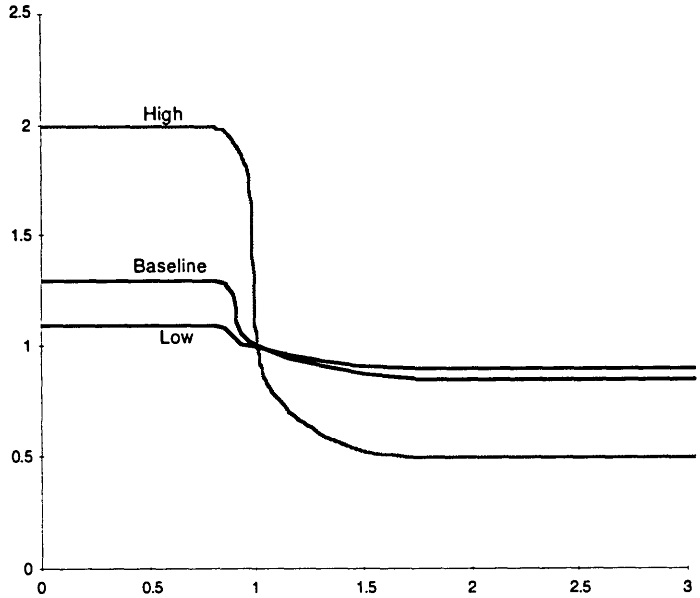

Figure A.14 Effect of Schedule Pressure on Productivity Function. As the percent perceived progress decreases, productivity increases because people work harder to try to meet the deadline. As the percent perceived progress increases, productivity decreases because people relax more. When the percent perceived progress is one, the effect on productivity is one.

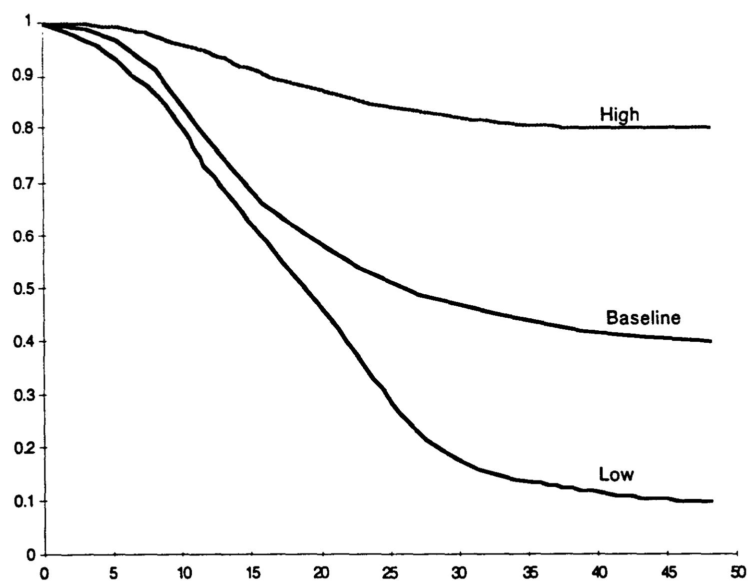

Figure A.15 Schedule Pressure Function. As time progresses, this function decreases the emphasis on the initial budget and increases the emphasis on the current budget.

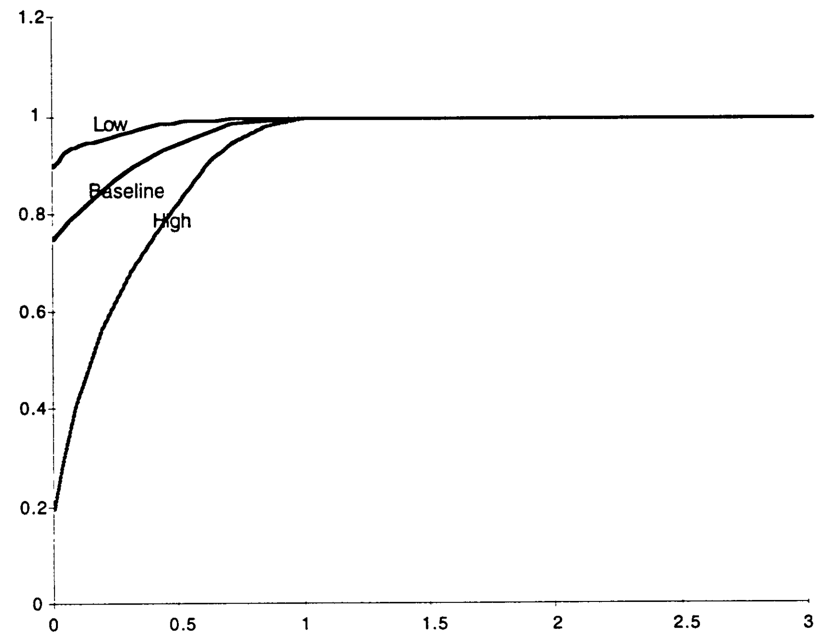

Figure A.16 Effect of Schedule Pressure on Quality Function. As schedule pressure increases, people work faster, which allows more mistakes to be made.

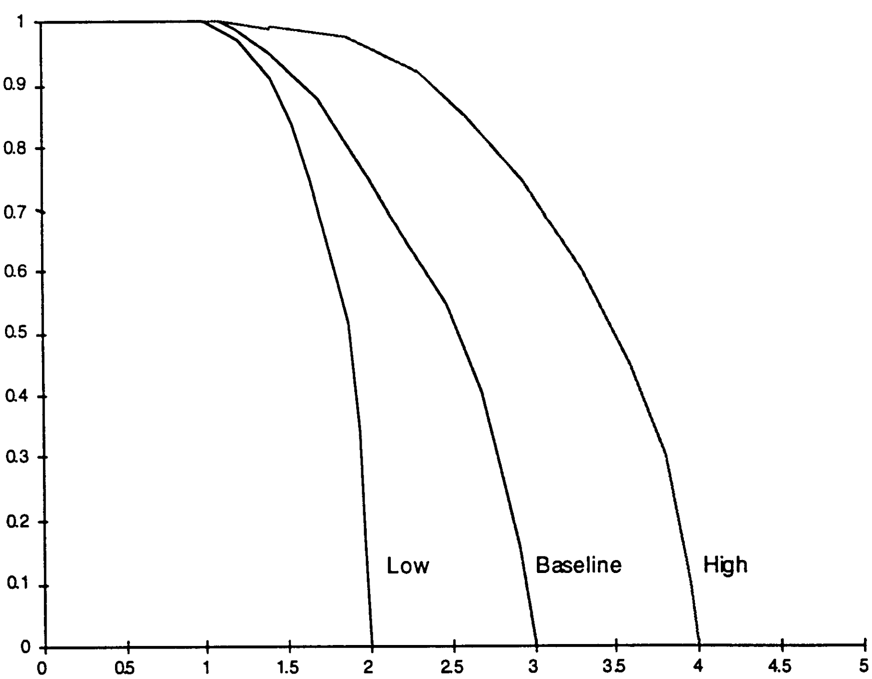

Figure A.17 Effect of Fatigue on Quality Function. When employees grow more fatigued, they become less conscientious, allowing more mistakes to be made. This decreases quality. When employees are less fatigued (normal fatigue equals one) quality of work increases.

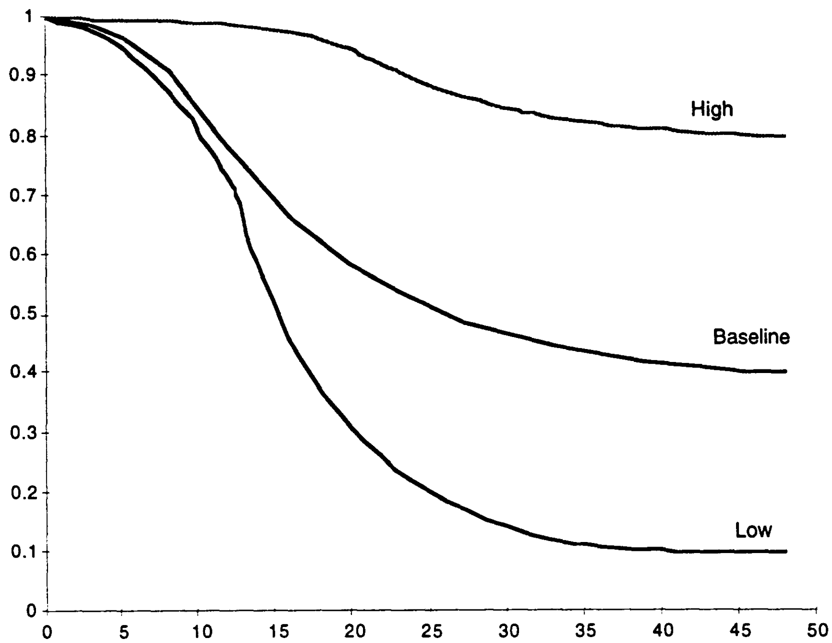

Figure A.18 Budget Pressure Function. As time progresses, this function increases the emphasis on the current budget and decreases the emphasis on the initial budget.

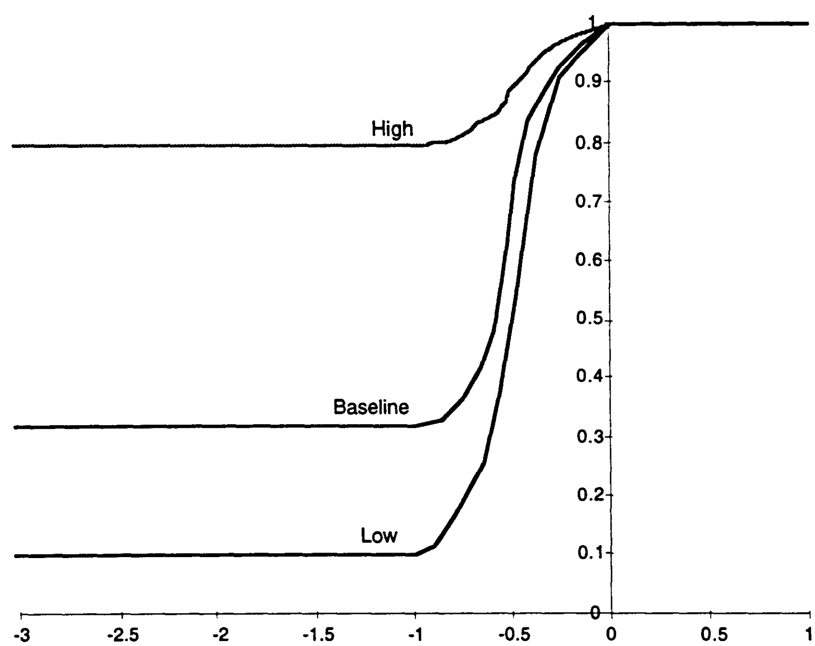

Figure A.19 Effect of Budget Pressure on Funding Change Function. Increasing budget pressure means the project is over budget. This function decreases future funding allocations dependent upon how far over budget the project is.

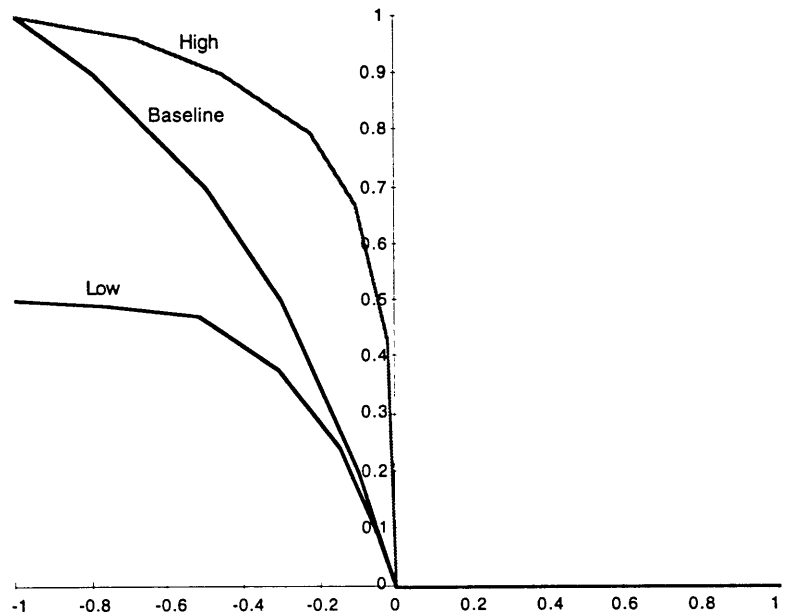

Figure A.20 Complexity Function. This function increases the complexity of changes (measured in person-hours of work) when the percent of changing funding decreases. When funding changes are zero or greater than one, there is no additional work added to the system.

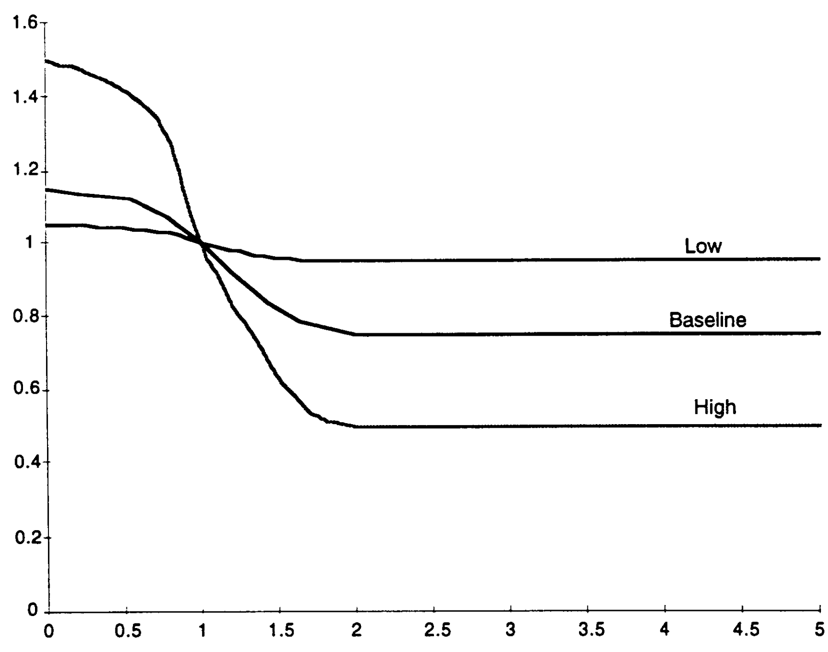

Figure A.21 Effect of Fatigue on Productivity Function. When employees grow more fatigued they are unable to complete as much work as they normally do, decreasing productivity. When employees are less fatigued (normal fatigue has a value of one) they are able to accomplish more, increasing productivity.

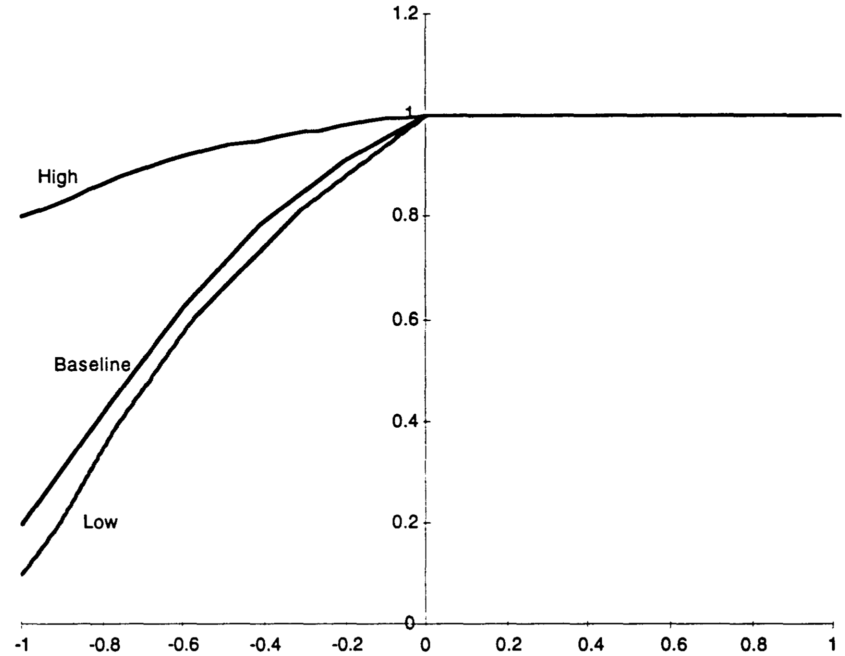

Figure A.22 Effect of Funding on Workforce Function. When project funding is decreased, this function decreases the workforce.

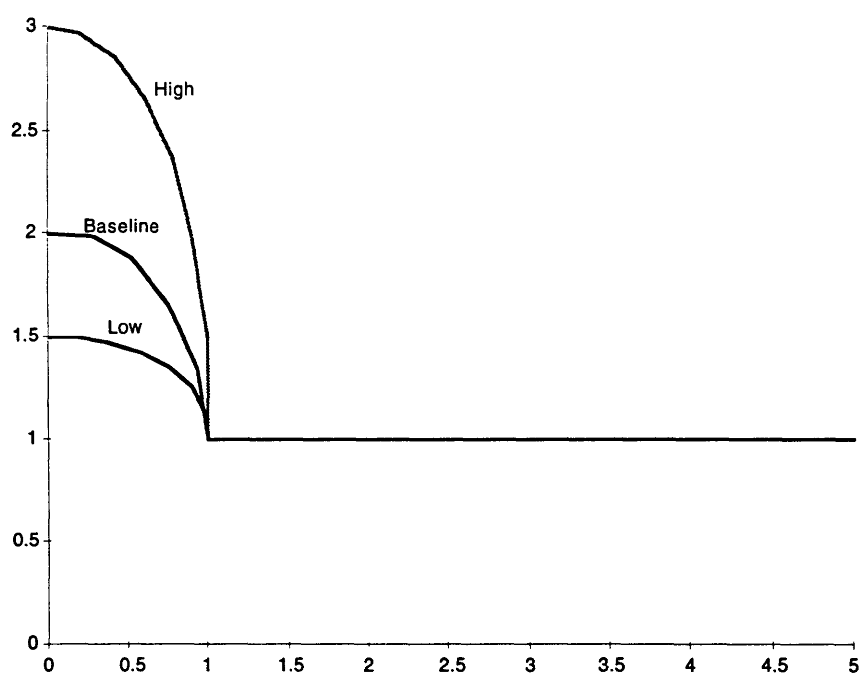

Figure A.23 Effect of Progress on Workforce Function. When the project is behind schedule, this function adds employees to the workforce. When the project is on or ahead of schedule, this function does not change the workforce size.

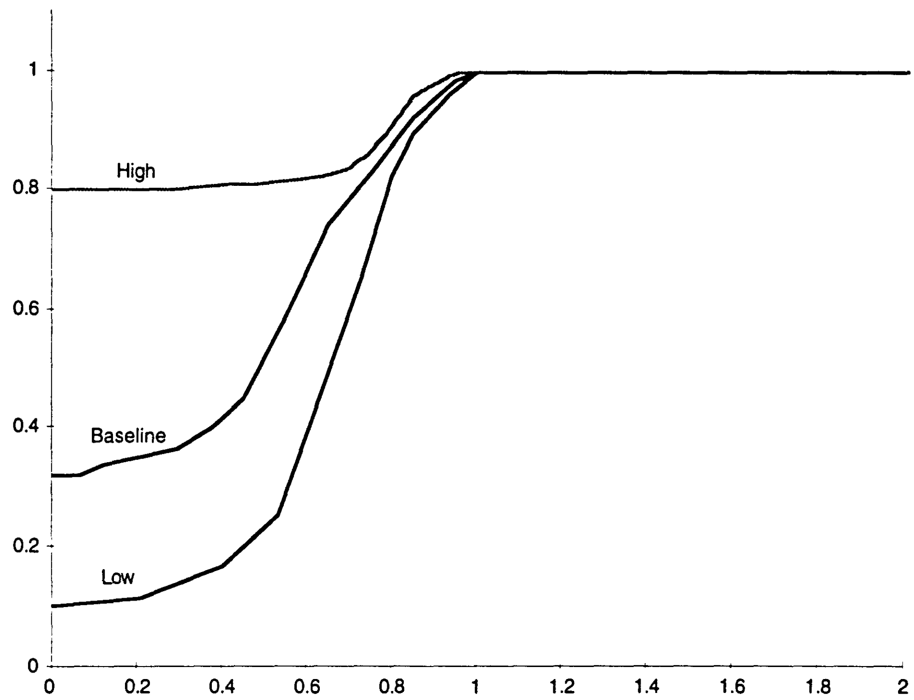

Figure A.24 Effect of Schedule Pressure on Funding Change Function. When the project falls behind schedule, this function decreases the future allocation of funding under the assumption that the entire military budget is decreasing. When the project is on or ahead of schedule, this function does not affect funding allocation.

A.4 Model: Text Format

Accruing Cost =OT Cost+standard time cost
~ Dollars/Month
~ Amount that the company charges to develop the project in a given month. |

accruing initial funding = IF THEN ELSE(Time<=time to do initially scheduled work,initial funding allocation stream,0)
~ Dollars/Month
~ Stops adding allocated funds when the project was initially supposed to be finished. |

Actual Funding = INTEG(total funding change, 0)
~ Dollars ~ |

Actual Product $ =INTEG(Accruing Cost,0)
~ Dollars ~ |

actual profile =MAX(initial profile+desired profile addition*effects on actual profile,0.01)
~ Dimensionless ~ |

adding changes = making changes
~ Person*hours/Month ~ |

allowable overtime = IF THEN ELSE(changing funding*(1+percent over budget allowance)<=PEOPLE*HOURS PER MONTH*development cost per person hour,(changing funding*(1+percent over budget allowance) /(PEOPLE*HOURS PER MONTH*development cost per person hour))-1, (changing funding*(1+percent over budget allowance)-PEOPLE* development cost per person hour * HOURS PER MONTH)/ (PEOPLE*HOURS PER MONTH*development cost per person hour*1.5))
~ Dimensionless
~ If funds plus over budget allowance are less than it costs to pay regular workers, allowable overtime is negative (cuts down regular time). If funds are greater, overtime is authorized. |

allowed schedule deviation = allowed schedule slip in percent*INITIAL WORK
~ Person*hours ~ |

allowed schedule slip in percent = 0
~ Dimensionless

~ Allowable slip in schedule before changes in personnel are made.
|

assigning work to do due to changes =MIN(Speed of Assigning Work*percent time assigning smooth*effective people*Productivity, Work Due to Changes/TIME STEP)
~ Person*hours/Month
~ Transferring changes into work. This step takes time, which is added to the total development time. |

basic funding overtime = IF THEN ELSE(changing funding<=PEOPLE*HOURS PER MONTH*development cost per person hour, (changing funding/(PEOPLE*HOURS PER MONTH*development cost per person hour))-1, changing funding/(PEOPLE*HOURS PER MONTH*development cost per person hour*1.5))
~ Dimensionless ~ |

Budget Pressure fn ([(0,0)-(300,1)], (0,1), (3.093,0.986), (5.155,0.965), (7.99,0.9126), (11.47,0.7937), (13.27,0.7413), (15.85,0.6643), (19.72,0.5874), (22.81,0.542), (27.06,0.486), (33.12,0.4476), (38.79,0.4196), (42.53,0.4091), (45.36,0.4021), (48,0.4),(300,0.4))
~ Dimensionless
~ As time progresses, this function decreases the emphasis on the budget. |

Budget Pressure on Funding Change fn ([(-5,0)-(1,1)], (-5,0.32), (-1,0.32), (-0.866,0.3322), (-0.7526,0.3671), (-0.6546,0.4196), (-0.5979,0.4825), (-0.5258,0.6259), (-0.4742,0.7413),(-0.4124,0.8357),(-0.3299,0.8916), (-0.2526,0.9301),(-0.1289,0.9685),(0,1),(1,1))
~ Dimensionless
~ As the project goes over budget, this function decreases the allocation of additional funding. |

CHANGES PER DOLLAR =30000
~ Dimensionless
~ Number of dollars of funding change that are required to make one person hour of additional work. |

changing funding = desired funding change
~ Dollars/Month ~ |

Complexity fn [(-1,0)-(5,1)],(-1,1),(-0.8,0.9),(-0.5,0.7),(-0.3,0.5),(-0.1,0.2), (0,0), (1,0), (5,0))

~ (Person*hours)/(Dollars/Month)
~ Complexity of changes vs %Changing Funding. As Funding Changes
drop to -1 (-100%), the complexity of changes is high. As Funding Changes approach zero, complexity of changes drop to zero. As Funding Changes go positive (more money to the project) the complexity of changes stays at zero, as there are no funding change driven changes.
|

complexity of changes =changing funding/CHANGES PER DOLLAR*

Complexity fn(percent changing funding)
~ Person*hours
~ How much extra work has to be done due to changes |

current budget pressure on funding change = Budget Pressure on Funding Change fn(percent gap actual funding and actual cost)
~ Dimensionless
~ If over current budget, this decreases the future funding allocation by multiplying by a value between zero and one. |

current schedule pressure on funding change approval = Schedule Pressure on Funding Change fn (percent perceived progress wrt current expected progress/REF TIME)
~ Dimensionless
~ If behind current schedule, this decreases the future funding allocation by multiplying by a value between zero and one. |

Current Work to Do = INTEG(adding changes-doing currently scheduled work-negated work due to changes,INITIAL WORK)
~ Person*hours ~ |

Currently Expected Progress = INTEG(doing currently scheduled work-negated work due to changes,0)
~ Person*hours ~ |

Delayed Fatigue = SMOOTH3(Fatigue,FATIGUE DELAY TIME)
~ Dimensionless
~ Smoothes the value of fatigue |

desired funding change = initial funding allocation stream*normal times effects on funding change
~ Dollars/Month
~ Amount of additional funding is desired. |

desired profile addition = MAX(1-percent perceived progress wrt current expected progress,0)/MONTHS PER YEAR
~ Dimensionless ~ |

development cost per person hour = INITIAL FUNDS ALLOCATED/ INITIAL WORK
~ (Dollars/Person)/hour ~ |

Discovered Rework =INTEG(discovering rework-reworking-negated rework due to changes,0)
~ Person*hours ~ |

discovering rework =MIN(Undiscovered Rework/DISCOVERY DELAY, Undiscovered Rework/TIME STEP)
~ Person*hours/Month ~ |

DISCOVERY DELAY = 4
~ Months
~ Time it takes to discover rework. |

doing currently scheduled work =ABS(NORMAL PEOPLE*initial profile/maximum percentage funding*HOURS PER MONTH)
~ Person*hours/Month ~ |

doing initially scheduled work = NORMAL PEOPLE*initial profile*HOURS PER MONTH/maximum percentage funding
~ Person*hours/Month ~ |

effect of budget pressure on funding change = Budget Pressure fn(Time)*initial budget pressure on funding change + (1 - Budget Pressure fn(Time))*current budget pressure on funding change
~ Dimensionless
~ Sum of initial and current budget pressures times percentage strength of each wrt time. The result of this equation is a value between zero and one. |

Effect of fatigue on PDY = Effect of Fatigue on PDY fn(Delayed Fatigue)
~ Dimensionless
~ As fatigue increases, productivity decreases. |

Effect of Fatigue on PDY fn ([(0,0.5)-(5,1.5)],(0,1.15), (0.2113,1.141), (0.5309,1.122), (0.7835,1.069), (1,1), (1.191,0.9243), (1.433,0.8339), (1.639,0.7796),(2,0.75),(5,0.75))
~ Dimensionless
~ More fatigued, less productive. |

Effect of Fatigue on Quality = Effect of Fatigue on Quality fn(Delayed Fatigue)
~ Dimensionless ~ |

Effect of Fatigue on Quality fn ([(0,0)-(5,1)], (0,1), (1,1), (1.1,1), (1.186,0.986), (1.402,0.9476), (1.655,0.8776), (1.851,0.8077), (2,0.75), (2.235,0.6469), (2.474,0.5455), (2.683,0.4021), (2.899,0.1573), (3,0), (5,0))
~ Dimensionless
~ More fatigued, less conscientious. |

Effect of Funding on Workforce fn ([(-1,0)-(3,1)],(-1,0.2), (-0.7887,0.4336), (-0.6031,0.6224),(-0.4124,0.7832),(-0.2062,0.9091), (0,1), (1,1), (3,1))
~ Dimensionless
~ As % changing funding decreases (i.e. more funds are removed from the project) the workforce is scaled back. |

effect of priority on funding change = PRIORITY
~ Dimensionless ~ |

Effect of Progress on Workforce fn ([(0,0)-(5,2)], (0,2), (0.2887,1.986), (0.5206,1.888), (0.7474,1.657),(0.9227,1.343),(1,1),(2,1),(5,1))
~ Dimensionless
~ When the project is behind schedule, the workforce is high. As the project gets back on schedule, the workforce is scaled back. |

effect of schedule pressure on funding change = Schedule Pressure fn(Time)*initial schedule pressure on funding change approval + (1-Schedule Pressure fn(Time))*current schedule pressure on funding change approval
~ Dimensionless
~ Sum of initial and current schedule pressures times percentage strength of each wrt time. The result of this equation is a value between zero and one. |

Effect Of Schedule Pressure On Productivity =Schedule Pressure fn(Time) * Effect Of Schedule Pressure On Productivity fn(percent perceived progress wrt initial expected progress) + (1-Schedule Pressure fn(Time))*Effect Of Schedule Pressure On Productivity fn(percent perceived progress wrt current expected progress)
~ Dimensionless
~ As the project falls behind schedule, people work harder, i.e. more productively. |

Effect Of Schedule Pressure On Productivity fn ([(0,0.75)-(5,1.5)], (0,1.3), (0.8,1.3), (0.8505,1.285),(0.8866,1.237), (0.8968,1.187), (0.9021,1.119), (0.9175,1.056), (0.9588,1.023), (1,1), (1.124,0.9528), (1.304,0.9163), (1.495,0.883), (1.763,0.8598),(1.899,0.8531),(2,0.85),(5,0.85))
~ Dimensionless
~ As percent perceived progress decreases, productivity goes up. People work harder to meet the deadline. As percent perceived progress goes up, productivity decreases as people relax more. At %pp = 1, effect on PDY = 1. |

Effect of Schedule Pressure on Quality = Schedule Pressure fn(Time)*Effect of Schedule Pressure on Quality fn(percent perceived progress wrt initial expected progress)+(1-Schedule Pressure fn(Time))*Effect of Schedule Pressure on Quality fn(percent perceived progress wrt current expected progress)
~ Dimensionless
~ As the project falls behind schedule, people work faster, decreasing quality. |

Effect of Schedule Pressure on Quality fn ([(0,0.5)-(6,1)], (0,0.75), (0.06443,0.7893), (0.1675,0.8392),(0.2474,0.8715),(0.3196,0.8995), (0.4381,0.9336), (0.567,0.9598),(0.7088,0.9834),(0.8531,0.993),(1,1),(5,1))
~ Dimensionless
~ As schedule pressure increases, quality of work decreases. |

effective people =PEOPLE*(1+Overtime)
~ Person ~ |

effects on actual profile = Effect of Funding on Workforce fn(percent changing funding)*Effect of Progress on Workforce fn(percent perceived progress wrt current expected progress)
~ Dimensionless ~ |

FATIGUE DELAY TIME = 1
~ Months ~ |

gap between actual funding and actual cost = Actual Funding-Actual Product $
~ Dollars
~ Gap between the currently allocated funds (initial plus changes) and the project's actual cost |

gap between initial funding and actual cost = Initial Funding-Actual Product $

~ Dollars
~ Gap between the initially allocated funds and the actual project cost |

gap current vs perceived progress = Currently Expected Progress-Perceived Progress
~ Person*hours
~ How far off of the current schedule? Negative, ahead of schedule. Positive, behind schedule. |

gap current vs work done right = Currently Expected Progress-Work Done Right
~ Person*hours ~ |

gap initial vs work done right = Initially Expected Progress-Work Done Right
~ Person*hours
~ |

initial budget pressure on funding change = Budget Pressure on Funding Change fn(percent gap initial funding and actual cost)
~ Dimensionless
~ If over current budget, this decreases the future funding allocation by multiplying by a value between zero and one. |

Initial Funding = INTEG(accruing initial funding,0)
~ Dollars ~ |

initial funding allocation stream =(INITIAL FUNDS ALLOCATED*initial profile/REF MONTH)/MONTHS PER YEAR
~ Dollars/Month ~ |

INITIAL FUNDS ALLOCATED =1e+010
~ Dollars
~ Total funding approved by Congress at the start of the project. |

initial profile = STEP(0.08,0) - STEP(0.08,12) + STEP(0.27,12)-STEP(0.27,24) + STEP(0.33,24) - STEP(0.33,36) + STEP(0.21,36) -STEP(0.21,48) + STEP(0.07,48) - STEP(0.07,60) + STEP(0.04,60)
~ Dimensionless ~ |

initial schedule pressure on funding change approval =Schedule Pressure on Funding Change fn(percent perceived progress wrt initial expected progress/REF TIME)
~ Dimensionless

~ If behind initial schedule, this decreases the future funding allocation by multiplying by a value between zero and one. |

INITIAL WORK =630000
~ Person*hours
~ Initial work to do to complete the project. |

Initially Expected Progress = INTEG(doing initially scheduled work,0)
~ Person*hours
~ How much work should have been completed by this time. |

making changes =complexity of changes/TIME TO MAKE CHANGES
~ Person*hours/Month ~ |

maximum percentage funding = 0.33
~ Dimensionless
~ Percentage of total funding in FY with the largest percent of funding. |

MONTHS PER YEAR = 12
~ Dimensionless ~ |

negated rework due to changes = IF THEN ELSE(Discovered Rework<=0,0, IF THEN ELSE(Work Due to Changes=0,0, MIN(PERCENT OF WORK CHANGED DUE TO FUNDING CHANGE*making changes, Discovered Rework/TIME STEP)))
~ Person*hours/Month
~ Rework that does not need to be done because changes have made the incorrect work no longer applicable to the project. |

negated work due to changes = IF THEN ELSE(Work Done Right<=0,0, IF THEN ELSE(Work Due to Changes=0,0,MIN(PERCENT OF WORK CHANGED DUE TO FUNDING CHANGE * complexity of changes, Work Due to Changes/TIME STEP)))
~ Person*hours/Month
~ Work that is no longer correct due to changes |

NORMAL PEOPLE = 100
~ Person
~ Total pool of people for the project |

NORMAL PRODUCTIVITY =172
~ Person*hours/Person/Month ~ |

NORMAL QUALITY r = 0.9
~ Dimensionless ~ |

NORMAL QUALITY w =0.8
~ Dimensionless ~ |

normal times effects on funding change =effect of budget pressure on funding change*effect of priority on funding change * effect of schedule pressure on funding change
~ Dimensionless
~ Adjustment to budget changes. |

OT Cost = IF THEN ELSE(Overtime>0, Overtime*PEOPLE*HOURS PER MONTH*development cost per person hour*1.5,0)
~ Dollars/Month
~ Calculates OT cost only if there is overtime, otherwise zero. |

over budget funds = IF THEN ELSE(Overtime>=basic funding overtime,

IF THEN ELSE(Overtime>0,Overtime*PEOPLE*development cost per person hour*HOURS PER MONTH*1.5 + (PEOPLE*development cost per person hour*HOURS PER MONTH-changing funding), (Overtime-basic funding overtime)*PEOPLE*development cost per person hour*HOURS PER MONTH),0)
~ Dollars/Month ~ |

Perceived Progress =Work Done Right+Undiscovered Rework
~ Person*hours ~ |

percent changing funding =ZIDZ((changing funding-accruing initial funding),accruing initial funding)
~ Dimensionless
~ Percent that funding has changed. Positive - funding increase over initial allocation. Negative - funding decrease over initial allocation.
|

percent gap actual funding and actual cost = ZIDZ(gap between actual funding and actual cost,Actual Funding)
~ Dimensionless
~ negative means over budget. positive means under budget. |

percent gap initial funding and actual cost = ZIDZ(gap between initial funding and actual cost,Initial Funding)
~ Dimensionless

~ Negative, Percentage over initial budget. Positive, Percentage under initial budget. |

PERCENT OF WORK CHANGED DUE TO FUNDING CHANGE =0.25
~ Dimensionless ~ |

percent over budget allowance = 0.05
~ Dimensionless
~ percent of funding allocation the company can go over budget.
|

percent perceived progress wrt current expected progress =xIDZ(Perceived Progress,Currently Expected Progress,1)
~ Dimensionless
~ percent perceived progress is one at time zero. |

percent perceived progress wrt initial expected progress =xIDZ(Perceived Progress,Initially Expected Progress,1)
~ Dimensionless
~ percent perceived progress is one at time zero. |

percent time assigning smooth = SMOOTH(percent time assigning work,TIME DELAY)
~ Dimensionless
~ Smoothing percentage of time to assign work. |

percent time assigning work = IF THEN ELSE (Work Due to Changes>0,0.15,0)
~ Dimensionless ~ |

percent time doing work = 1-percent time assigning smooth-percent time reworking smooth
~ Dimensionless ~ |

percent time reworking =IF THEN ELSE(Discovered Rework=0,0,

IF THEN ELSE(Work to do/INITIAL WORK<=0.05,0.95,0.15))
~ Dimensionless
~ Percent Time Reworking is zero until discovered rework is greater than zero. |

percent time reworking smooth = SMOOTH(percent time reworking,TIME DELAY)
~ Dimensionless ~ |

PRIORITY = 1
~ Dimensionless
~ How important the project is considered. 0 - no additional funding. 1 - initially allocated additional funding. 2 - twice initially allocated additional funding. |

Productivity = NORMAL PRODUCTIVITY * Effect of fatigue on PDY * Effect Of Schedule Pressure On Productivity
~ Person*hours/Person/Month ~ |

quality r = NORMAL QUALITY r*Effect of Schedule Pressure on Quality*Effect of Fatigue on Quality
~ Dimensionless ~ |

quality w =NORMAL QUALITY w*Effect of Fatigue on Quality*Effect of Schedule Pressure on Quality
~ Work/Work
~ % of work done correctly |

REF MONTH = 1
~ Month ~ |

REF TIME = INITIAL(1)
~ Month ~ |

rework being done correctly = reworking*quality r
~ Person*hours/Month ~ |

rework being done incorrectly = reworking*(1-quality r)
~ Person*hours/Month ~ |

reworking =IF THEN ELSE(Discovered Rework<=0,0,MIN(SPEED OF REWORKING*percent time reworking smooth*effective people*Productivity,Discovered Rework/TIME STEP))
~ Person*hours/Month ~ |

Schedule Pressure fn ([(0,0)-(300,1)],(0,1), (3.093,0.986), (5.155,0.965), (7.99,0.9126), (11.47,0.7937),(13.27,0.7413), (15.85,0.6643), (19.72,0.5874), (22.81,0.542), (27.06,0.486),(33.12,0.4476), (38.79,0.4196), (42.53,0.4031), (45.36,0.4021),(48,0.4),(300,0.4))
~ Dimensionless
~ As time progresses, this function decreases the emphasis on the schedule. |

Schedule Pressure on Funding Change fn ([(0,0)-(5,1)], (0,0.32),
(0.06701,0.3217), (0.1856,0.3392),(0.2938,0.3636), (0.3763,0.4021),
(0.45,0.45), (0.55,0.59),(0.65,0.74),(0.75,0.83), (0.85,0.92), (0.95,0.985),
(1,1), (5,1))
~ Dimensionless
~ As the project falls behind schedule, this function decreases the future allocation of funding. On or ahead of schedule is one. |

Speed of Assigning Work = 3
~ Dimensionless ~ |

SPEED OF REWORKING = 2
~ Dimensionless
~ Multiplier times basic working rate, reworking can be done faster or slower than regular work. |

standard time cost = IF THEN ELSE(Overtime>=0, PEOPLE*HOURS PER MONTH*development cost per person hour, (1 + Overtime) *PEOPLE* HOURS PER MONTH*development cost per person hour)
~ Dollars/Month
~ If there is overtime, charge for max standard hours. If overtime is negative, charge only for people working. |

TIME DELAY =2
~ Month ~ |

time to do initially scheduled work = 72
~ Months ~ |

TIME TO MAKE CHANGES = 1
~ Month ~ |

total funding change = changing funding+over budget funds
~ Dollars/Month ~ |

Undiscovered Rework =INTEG(work being done incorrectly+rework being done incorrectly-discovering rework,0)
~ Person*hours ~ |

work being done =MIN(percent time doing work*effective people* Productivity, Work to do/TIME STEP)
~ Person*hours/Month ~ |

work being done correctly =work being done*quality w
~ Person*hours/Month ~ |

work being done incorrectly =work being done*(1-quality w)
~ Person*hours/Month ~ |

Work Done = INTEG(work being done+reworking,0)
~ Person*hours
~ All person hours of work done, right, wrong, or rework |

Work Done Right =INTEG(work being done correctly + rework being done correctly - negated work due to changes,0)
~ Person*hours ~ |

Work Due to Changes = INTEG(-assigning work to do due to changes + making changes,0)
~ Person*hours
~ Extra work that must be done due to changes. |

Work to do = INTEG(assigning work to do due to changes-work being done - negated work due to changes, INITIAL WORK)
~ Person*hours
~ Person-hours of work that remain to be done |

****

.Control

**~

Simulation Control Parameters |

FINAL TIME = IF THEN ELSE(Work to do/(INITIAL WORK+Work Due to Changes)>0.05,1000, IF THEN ELSE(Work Done Right/(INITIAL WORK+Work Due to Changes)<0.95,1000,Time))
~ Month
~ The final time for the simulation. |

INITIAL TIME = 0
~ Month
~ The initial time for the simulation. |

SAVEPER =
TIME STEP
~ Month
~ The frequency with which output is stored. |

TIME STEP = 0.25
~ Month
~ The time step for the simulation. |

****

.ot/fatigue

**~

|

desired people = MAX((gap initial vs perceived progress-allowed schedule deviation),0)/HOURS PER MONTH/REF MONTH

~ Person ~ |

Fatigue = INTEG(Getting Fatigued,1)

~ fraction ~ |

gap initial vs perceived progress =Initially Expected Progress-Perceived Progress

~ Person*hours

~ How far off of the initial schedule? |

Getting Fatigued = (Overtime - (Fatigue-1)) / Time To Get Fatigued

~ fraction / Month ~ |

HOURS PER MONTH = 172

~ hours/Month

~ Dimensionless 72 hours per month, 40 hours per week, 4.3 weeks per month |

indicated overtime = desired people/PEOPLE

~ Dimensionless ~ |

Overtime =MIN(indicated overtime,allowable overtime)

~ Dimensionless

~ Multiplier for how many times a person works. 0=no overtime, 1=100% more overtime, 2=200% more overtime, -1=-95% ot - standard work is decreased to 5% of initial. |

PEOPLE =NORMAL PEOPLE*actual profile/maximum percentage funding

~ Person ~ |

Time To Get Fatigued = 1

~ Month ~ |

APPENDIX B

REFERENCES

Acquisition of Major Weapon Systems. Report to Congress by the Comptroller General of the United States: 1971.

Adams, Gordon. The Politics of Defense Contracting: The Iron Triangle. Transaction Books: New Brunswick, 1981.

Augustine, Norman R. Augustine's Laws. Viking Books: New York, New York, 1986.

Battershell, Lee. The History of the C-17. Unpublished.

Biddle, Wayne. Barons of the Sky. Simon & Shuster: New York, NY, 1991.

Cooper, Kenneth. "The Rework Cycle: Why Projects are Mismanaged." PMNetwork February–March, 1993.

Drezner, Jeffrey A., Giles K. Smith, et. al. Maintaining Future Military Aircraft Design Capability. The RAND Corporation: Santa Monica, CA, 1992

Federal Budget of the United States, 1996. Office of Management and Budget. Superintendent of Documents, Washington, DC, 1996. http:// www.doc.gov/inquery/BudgetFY96/pdf/bud96g.pdf.

Forrester, Jay W. "Common Foundations Underlying Engineering and Management." The Institute of Electrical and Electronics Engineers, Inc. September, 1973: p. 66-77.

Forrester, Jay W. Counterintuitive Behavior of Social Systems." Technology Review 73, 1971: p 52-68.

Forrester, Jay W. Industrial Dynamics. Cambridge, MA: Productivity Press, 1961.

Gansler, Jacques S. Affording Defense. Cambridge, MA: MIT Press, 1989.

Gansler, Jacques S. The Defense Industry. Cambridge, MA: MIT Press, 1980.

Gregory, William H. The Defense Procurement Mess. Lexington Books: Lexington, MA, 1989.

Gulledge, Thomas R. and Norman K. Womer. The Economics of Made-to-Order Production. Springer-Verlag: Berlin, Germany, 1986.

Historical Tables. United States Federal Budget. Office of Management and Budget. Superintendent of Documents, Washington, DC, 1996. http:// www.doc.gov/inquery/BudgetFY96/pdf/bud96h.pdf.

History of the American Aircraft Industry. Editor G.R. Simonson. The MIT Press: Cambridge, MA, 1968.

Holly, Irving Brinton Jr. Buying Aircraft: Materiel Procurement for the Army Forces. Office of the Chief of Military History, Department of the Army: Washington, DC: 1964.

Homer, Jack B. "Worker Burnout: A Dynamic Model with Implications for Prevention and Control." System Dynamics Review Summer 1985: pp. 46-62.

The Impact of Reduced Defense Spending on U.S. Defense Contractors. Report of the Defense Conversion Committee. DRI/McGraw Hill: Washington DC: 1993.

Kaufman, Allen. "In the Procurement Officer We Trust: Constitutional Norms, Air Force Procurement, and Industrial Organization, 1938-1948". Defense and Arms Control Studies Program, MIT. Cambridge, MA.

Kim, Daniel H. "Toolbox: Guidelines for Drawing Causal Loop Diagrams." The Systems Thinker February 1992: pp. 5-9.

Little, John D. C. "On Model Building". Ethics in Modeling. Ed. William A. Wallace. Troy, NY: Pergamon, 1994.

Oreskes, Naomi, Kristen Shrader-Frechette, and Kenneth Belitz. "Verification, Validation, and Confirmation of Numerical Models in the Earth Sciences." Science February 4, 1994: pp. 641-646.

Paich, Mark and John D. Sterman. "Boom, Bust, and Failures to Learn in Experimental Markets." Management Science December 1993: pp. 1439-1458.

Political Economy of Military Spending. Editor Alex Mintz. Routledge: London, UK., 1992.

Sastry, M. Anjali and John D. Sterman. "Desert Island Dynamics: Am Annotated Survey of the Essential System Dynamics Literature." Proceedings of the

1993 International System Dynamics Conference. Ed. E. Zepeda and J. Machuca. Cancún, Mexico, 1993. pp. 466-475.

Sterman, John D. "Learning in and About Complex Systems." February, 1994.

Sterman, John D. "The Meaning of Models." Letter to the Editor. Science April 15, 1994: pp. 329-331.

Sterman, John D. "Modeling Managerial Behavior: Misperceptions of Feedback in a Dynamic Decision Making Experiment." Management Science 35(3) 1989: p.321-339.

Tagliaferre, Lewis. Understanding Aerospace Marketing. Data Publications: Washington DC, 1968.

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