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Dynamics of Naval Ship Design: A Systems Approach

ABSTRACT

In today's cost-constrained environment, acquisition reform is a critical component in the design, production and support of modern warships. This reform includes policies that require system acquisition programs to pursue commercial management and systems engineering practices. The application of Integrated Product and Process Development (IPPD), concurrent engineering, open systems architecture, Total Quality Management (TQM) and Integrated Design Environments (IDE) have produced noteworthy commercial successes. Many defense acquisition programs have followed suite, implementing similar process improvements. However, as many commercial industries are finding, there are limits to the success of these improvements. For example, TQM improvements are frequently not repeatable in other organizations, or even within the same organization. These failures are partly due to a lack of understanding of the dynamic impacts of process improvements within an organization, and the lack of strategic metrics and structures to monitor and optimize the improvement process. To effectively implement improvements, it is necessary to pursue a methodical, focused improvement plan.

Using the methods of System Dynamics, this paper examines the mechanisms which have lead to program instabilities in cost, schedule, and effectiveness. The 1990 Naval Sea Systems Command (NAVSEA) Ship Design, Acquisition and Construction (DAC) Study analyzed process specific issues, and developed metrics for optimizing ship performance, cutting acquisition cost, and reducing design cycle time. The results of this study, and additional data collected from past and current ship acquisition programs are used to model the ship design and production process with the goal of "gaming" process improvements relative to performance metrics. Specific mechanisms studied include:

- external influences such as increased technological complexity and budgetary pressures;
- internal process delays such as information flow delays and approval delays; and
- feedback processes such as design iteration, error propagation and design change.

Modeling of these mechanisms provides a means to study past programs, and assess the potential savings that can be generated with the introduction of process improvements.

As a case study, the paper examines the structures and resultant trends that impacted the design and acquisition of DDG 51. General process structures are studied including design interactions, schedule, resources, and allocation. Specific dynamic relationships between cost thresholds, design effort and schedule are studied to show the ability of modeling to capture dynamic trends and predict results. Finally, a "what-if?" scenario that looks at the application of IPPD is examined. The scenario demonstrates the potential for process optimization, and identifies critical variables and areas of risk.

Introduction

In 1990, then Naval Sea Systems Command (NAVSEA) Chief Engineer, RAdm Roger Horne, initiated the design, acquisition and construction (DAC) project. The objective of DAC was to apply rigorous process analysis to naval acquisition. The analysis demonstrated the need for significant change in the naval ship design process to reverse alarming trends in cost and schedule. Prior to this study, design focus was aimed at improving performance, but cost and schedule were treated as less critical. There is little argument that the performance and capabilities of surface combatants improved exponentially from the FFG 7 class ships of the 1970’s to the current generation of DDG 51 Flight IIA ships. However, as Figure 1 and Figure 2 demonstrate, achieving these leaps in performance resulted in greater and greater sacrifices in acquisition cost and cycle time. Basic Construction Costs (BCC) for surface combatants, inclusive of learning curve effects, have increased at about $10 million/year. Conceptual Design time (concept design and preliminary design) has increased at a rate of 1.5 months per year while Contract Award time (from program start through completion of contract design) and Time to Deliver have increased at a rate of 3 months per year and 5 months per year respectively. These trends, coupled with exponentially increasing man-day efforts required to deliver ship designs, are disturbing as they represent a barrier to providing warfighters with timely, affordable systems necessary to meet future threats. It is to these trends that the Navy has focused its own acquisition reform effort during the decade since DAC. Specifically, the focus in design efforts have changed "to identify the critical actions necessary to improve the quality of future ship designs, to reduce ship costs, and to reduce the cycle time required from establishment of requirements to delivery of the lead ship (Horne 1991).

Reform of naval design programs has paralleled the larger effort to modernize all acquisition programs within the Department of Defense (DOD). Reacting to many of the same trends disclosed in naval programs, DOD initiated the acquisition reform effort to optimize fiscal and temporal resources in light of continued need to modernize US defense capabilities. Specific reforms include:

- revision of Department of Defense (DOD) acquisition process and contract requirements delineated in DOD Instructions 5000.1 and 5000.2,
- reengineering of the acquisition process to be inclusive of not only government capabilities but commercial expertise and customer needs, and
- application of advances in information technology through the use of open systems architecture, simulation based design (SBD), and Integrated Product Models.

Generally, these reforms are categorized under the umbrella of commercial practices. For instance, reform efforts now require the maximum use of Integrated Product and Process Development (IPPD). By IPPD, multi-disciplinary teams, representing all potential elements of design, production, and life-cycle support, examine all aspects of the design (requirements, technology alternatives, cost, ILS, manning, etc) as early as possible in the design process. The methodology builds on the premise that the greatest leverage for life-cycle cost savings is only achievable in initial development, when the design is most flexible to change. This method has been successfully exercised in the commercial sector in development projects ranging from software to automobiles. In turn, the use of IPPD has been applied to defense projects ranging from the Ship Self Defense System (SSDS) program to the New Attack Submarine (NSSN) program (Acquisition Reform Office, 1998).

Recognizing the Positive and Negative Impacts of Process Improvements

Critical to understanding the implementation of such process improvements is the recognition of the multiple, objective influences any one methodology will cause. For instance, integral to IPPD is concurrent engineering in which design tasks relating to manufacturing are considered early in the design. To facilitate such efforts, concept designs must possess greater information fidelity to accommodate these design tasks. Although the communication of ideas does improve the design, early participation of manufacturing and support agents often raises questions of proprietary boundaries. An additional element to IPPD is the use of 3D Product Modeling to integrate 3D geometry, associative and parametric relationships and non-geometric information into a single model to be employed from concept design through ultimate ship disposal (Baum and Ramakrishnan, 1997). Such modeling enables IPPD team members to effectively communicate design information and capture knowledge about the design. However, use of complex databases as well as efforts required to generate the associated increase in early design information requires an order of magnitude increase in early funding over traditional approaches. This is a substantial barrier considering the typical aversion to fiscal risk for R&D efforts. Culturally, IPPD requires a fundamental restructuring of the design and approval organization, increased use of teaming skills vice individual innovation, and application of management techniques such as Quality Functional Deployment (QFD) and Earned Value Management (EVM). This sampling of process improvement elements demonstrates the diversity of changes imposed by the full application of a single improvement effort and raises the question: how does one optimize the application of process improvements and, perhaps more importantly, avoid potential negative results often seen in such efforts?

In order to answer these questions, is necessary to obtain objective measures of improvement effectiveness. However, in very long R&D efforts, such real-time knowledge is extremely hard to capture. Consider naval ship acquisition, which is unique within the constrained framework of the Department of Defense (DOD) and Department of the Navy (DON) organizations. Navy ships are bought in small quantities, have very long development cycles, and are extremely costly…precluding the "fly before you buy" approaches required for purchase of other weapon systems. The typical duration for combatant ship design can exceed 12 years and official DOD timelines (satisfying all program requirements) can exceed 22 years (Ryan and Jons, 1991). Over such an extended period, it is difficult to assess how a specific process improvement will respond to fluctuating funding, political and organizational transitions, and changing military threats. Thus, the lessons learned from process improvements within programs such as DD 21, NSSN or LPD 17 may be neither fully recognized for years nor transferable to future programs due to long term changes in the socio-political environment.

The final issue to consider in process improvement regards the source of improvement failures. Senge (1990) points out that the failure of many process improvement initiatives in the United States is less a consequence of cultural bias as the result of ignorance of the systemic impacts of those initiatives as implemented. In other words, the expectations did not meet results because improvements were not properly tailored to the process being effected. For instance, Total Quality Management (TQM) has been prescribed as a method to provide process improvement for organizations within DOD and industry. Unfortunately, misunderstandings and unrealistic expectations can often derail well-intended improvement efforts under TQM. Consider the case of Analog Devices (Kaplan, 1990). The company pursued an aggressive TQM based process improvement effort on the factory floor in order to regain a competitive edge in the semiconductor business. The results were notable during the five year period from 1987 to 1992: reduction of manufacturing cycle time from 15 weeks to 4 weeks, process defects reduced from 5000 PPM to 10 PPM, and yield increased from 20% to over 50%. However, attempts to produce similar improvements in the design process were not repeatable. Consider Figure 3. For an organization with fixed assets to implement improvements, it may be assumed that the initial allocation of support to manufacturing and design is evenly split at 50-50. The levels of improvement activity are directly linked to the levels of support. As improvement activity increases, the required support to maintain activity will likewise increase as managers and employees become reliant on those improvements. If both sectors improved equally, the process would be balanced. However, as one sector generates improvements, then that sector will rally support for additional resources, eventually choking resources from the other. This was the observation at Analog Devices. The observed half-life for manufacturing improvements (i.e. the time to realize a 50% improvement over the previous increment) was 9 months. The half-life for design improvement efforts is 2 to 3 years. Thus left unchecked, the momentum of the manufacturing sector dominated the improvement resources denying the design sector the opportunity to succeed. The morals of the story: process improvements must be tailored and supported within the context of the process, and policy levers meant to improve a process may be detrimental when viewed within the context of long range dynamic impacts. It is to the dilemma of improvement failure, the prohibitive real-time comparisons of individual improvement efforts, and the questions of process optimization that new generations of process simulation offer a solution.

Simulating Design Processes

Traditional Project Modeling

There are many modeling and management tools available to simulate design and acquisition projects. Consider some traditional project management methods listed in Table 1. These methods focus primarily on operational issues necessary to define project work structure, resource availability and requirements, and budget needs and allocations. The approaches assume a well ordered project that progresses in well-defined stages to completion. The techniques assume a sequential or, as in the case of PERT, limited feedback structure. Process structure does play a role for creation of these models enabling analysis of critical work paths and schedule compression schemes. However, the models rely heavily on historical data to capture indirect process influences such as the effects of productivity, rework or multiple concurrent activities. For example IDEF models of preliminary design tasks for a simple ship design predict reduction of design time by almost 40% (Tan and Bligh, 1998). Through an assumption of complete decoupling, the model demonstrates those design functions that may be performed concurrently vice sequentially. However, the IDEF compression ignores the impacts of restructuring as regards productivity issues like error propagation and design rework.

Traditional methods can account for some productivity issues, but this requires the use of substantial detail about the development process. Such detail is often lacking in the early stages of naval ship development. When detail is available, it may be difficult to determine strategic impacts from the multitude of operational decisions available in such models. Analysis often fails to detect systemic impacts of a given process improvement or realize strategic goals for improvement processes (Rodrigues and Bowers, 1996). These methods fail to capture decision process logic, socio-political factors, workplace environment and other human factors. They do have value in the operational management of a design process, but are limited in their ability to address strategic issues.

System Dynamics

An alternative modeling approach is the use of system dynamics. System dynamics is an application of traditional engineering techniques of control theory and feedback analysis. Three characteristics distinguish system dynamics from traditional management support tools (Alfeld, 1994):

- Founded in engineering science, not statistics,
- Relies on process structure rather than process data to control model development
- Leverages dynamic, vice static, execution environment.

System dynamics demands the development of models that capture the process of a system. These process-based models build on explicit casual relationships of variables within a closed-loop feedback structure. Direct input variables are limited to exogenous forces that are defined and effected outside the boundaries of the system. The majority of variables are generated and effected endogenously by system structure. For example, the nominal productivity of an engineer is a function of human capabilities. A system capturing the number of drawings produced by a process, would accept nominal productivity as input, but realized productivity would be generated by internal forces such as drawing backlog, overtime, schedule pressure and quality of work. Historical data is used to calibrate the model, but the verification of a model relies on common sense (agreement of the operation of the real world and the model structure) and formal mathematics (accumulations and flows based in differential calculus.) For the same example, nominal productivity in static models would ordinarily be represented as a distribution of productivity whose expected values are correlated to internal process forces such as those noted above. The system dynamics approach relies on the interrelationship of those forces to a calibrated input value for nominal productivity to capture the observed trends. In other words, the correlation becomes a physical relationship rather than statistically based. The resulting model relies on complex, non-linear relationships to dictate behavior, rather than linear, statistically based associations. System dynamics models do incorporate statistics during analysis as a means to test the sensitivity of model assumptions. However, this analysis is intended to further validate the model rather than drive model development. Finally, model results are utilized as strategic tools to compare policy impacts, not produce explicit results (such as exact cost or a definitive timetable.) A validated model, which demonstrates generally accurate behavior (variable fluctuations, dynamic convergence or divergence, and representative process structure) provides a means to assess policy options for order of magnitude relationships and high leverage options.

The procedure for developing and analyzing a system dynamics model is well stated by Randers (1980). The procedure is applied in four stages:

1. Conceptualization
2. Formulation
3. Testing
4. Implementation

Conceptualization explores the problem to be modeled. This requires explicit definition of the problem. Definition provides a focus to the model, establishes specific boundaries of the system, and identifies key variables. Once defined, it is necessary to develop quantitative and qualitative trends, or behavior modes, for the variables of the problem. Trends demonstrate the observed, past behavior of the system, as well as the hypothetical range of future behaviors (decay, exponential growth, asymptotic, or cyclical) which dynamic structure may generate. With the variable dynamics displayed, it is possible to develop qualitative descriptions of feedback, or casual loops. Casual loops are hypothetical statements of the feedback structures in the system. Formulation is the process of translating hypothetical structures and variables from conceptualization into a mathematical model of the system. Procedurally, the key to this step is the determination of stocks and flows. Stocks are physical accumulations, or integrations, within the system. Flows are transfers, or differentials, between stocks. It is the differences and flows among stocks in the systems that create imbalances and, thus, dynamic behavior. The third step in modeling is testing. Testing is the iterative process of calibrating the model to demonstrate that the model effectively captures the dynamics displayed by the behavior modes. In testing it is important to focus on model structure as the source of behavior. The fourth step is implementation. Here, the model is examined through sensitivity analysis to demonstrate high leverage policy options. Further analysis can include process optimization and "what-if" scenarios. Note that the outcome of the modeling process is NOT prediction, but rather understanding of the potential futures generated by a policy action and responsiveness to changes as they are observed.

The Naval Design Process (NDP) Model

The NDP model was developed as an academic exercise to examine the following question: given a representative surface combatant development effort such as the DDG 51 program, could application of IPPD elements have resulted in substantial cycle time savings and what unforeseen outcomes may have been encountered. Answering this question provides insight for the optimization of current development efforts such as the DD 21 program.

Iteration and Design

It is important to consider the unique process of naval combatant design. The design of a ship is not the act of designing specific equipment…rather; it is the integration of systems and equipment to optimize cost and effectiveness (Gale and Scott, 1995). Such activity is inherently multi-disciplinary and highly iterative. However, this is not to say that the process is without repeatable structure and organization. To the contrary, the naval ship design process must follow very specific steps and satisfy fundamental physical laws in order to achieve a balanced design. These balanced properties range from the most basic (hydrostatic balance, resistance-to-powering balance, structural stress-to-integrity balance, etc) to those demanded for increased effectiveness and decreased cost (passive-vs. active-defense trade-off, hullform vs. producible design, etc).

Two key feedback concepts have been just been noted: iteration and balance. Iteration on the macro-scale parallels that of the general systems engineering process shown in Figure 4. The events from input requirements through system definition may proceed sequentially or in parallel. However, premature parallel development of downstream events may be superceded by changes in earlier stages. This results in generation of rework due to the coupling of the events. As regards balance, iteration is necessary by the degree of imbalance among levels. Specifically, effort is expended to optimize system objectives based on the needs of the customer, the constraints of the environment and the feasible solution space. This is both a management and an engineering-mathematical problem. The management side is extracting meaningful boundaries and constraints from the system players. The engineering-mathematical aspect is developing a physical solution to the given system variables that is a robust and accurate optimization of the needs.

The naval ship design process is an example of a system engineering process with the following elements:

- Establishing a military need (Pre-milestone 0)
- Defining this need in terms of military requirements and constraints (Pre-milestone 0 and Phase 0)
- Performing a set of design tasks to develop solutions (Phase 0)
- Validating the solution versus the requirements (Phase I Development)
- Translating the solution into a form usable for production and ship support (Phase II and beyond)

These structures and milestones, as defined by DOD Instruction 5000.1, will represent the strategic structure for development of the NDP model.

Modeling the Naval Design Spiral

On the operational level, iteration is defined by the design spiral. The design spiral describes the process that compartmentalizes the design disciplines and regiments the engineering steps necessary for a balanced design. (Note that the concept of the design spiral is attributed to Professor J.H. Evans of MIT and was first introduced in the Naval Engineers Journal, November 1959.) The spiral is characterized by a sequence of specific tasks that incorporate initial design requirements, synthesize these requirements into a set of design characteristics, assess the design characteristics against the requirements and against one another, and iterate as necessary to achieve convergence of the values. Design balance indicates the defined ship characteristics are physically stable while satisfying design requirements. It is important to note that a balanced design may not necessarily represent the optimal design (Andrew, 1998). There is no one spiral that is correct for all ship designs. A proposed spiral must incorporate design and analysis elements necessary to satisfy requirements. In particular, the spiral task elements may vary by mission requirements, level of risk mitigation required or level of sub-system and total system maturity. For those general design disciplines that are chosen for a given spiral, sub-spirals may be necessary within a design node in order to generate and analyze specific design characteristics. The consequence of layers of design and analysis is a set of nested iterations of design within the overall design structure. Additionally, the sequential description of the spiral is misrepresentative. Due to the interrelationships of design variables in non-sequential events, the spiral is actually a network or interaction mesh joining design nodes by physical relationships and information flows (Brown, 1993). The potential exists for an infinite number of feedback paths within the spiral. It is precisely for this reason that traditional process modeling techniques may fail to capture the true process structure.

The views of the systems engineering and naval engineering iterative networks are consistent with the basic structures for product development models utilized in system dynamics. Namely, the iterative nature reflects a necessity to take a set of initial (or baseline) tasks to be done, perform those tasks at given a level of effective productivity, and rework the tasks due to varying levels of design quality and adherence to requirements. Figure 5 shows an example of a project model structure. This project model structure is common to several specific project models including the Ingalls Litigation Model (Cooper, 1980), Program Management Modeling System (PMMS) (Pugh-Roberts Associates, 1997), Software Project Model (Abdel-Hamid and Madnick, 1991) and Concurrent Development Model (Ford and Sterman, 1997). Applied to modeling of naval design, "initial work to be done" is equivalent to the number of design nodes and tasks within the design spiral. Productivity is the rate of design accomplishment consistent with the number of designers assigned to and the complexity of the task. Quality may be interpreted as the rate of design convergence (i.e. the quantity of tasks requiring re-iteration.) Undiscovered rework and rework discovery represent the analysis steps of the design spiral. Known rework and rework accomplishment represent subsequent iterations of the spiral.

Capturing Complex Design Networks

The elemental structure of the project model is replicated and combined to represent complex interrelationships in the design network. Consider a typical set of naval design tasks (Figure 6). The design spiral for this set of tasks demonstrates the non-sequential events of the design process that are realized in the resultant non-linear schedule trends of design iterations and design deliverables for each iteration (Figure 7). Each task relies on different design disciplines (marine engineering, hydrodynamics, structural engineering, weight engineering, etc.) and generates individual convergence with varying mathematical structures (hull weight changes as L^2-L^3 and hull surface area increases as L^2, available horsepower varies as non-continuous step function, etc.) The required tasks may be organized into a Design Structure Matrix (DSM) (Eppinger, Whitney, Smith and Gebala, 1993). The matrix structure shown in Figure 8 for the previous design spiral demonstrates how design tasks are related, or coupled, by input and output relationships. These relationships can be assigned based on physical requirements of engineering as well as procedural requirements and structures applied by design managers. Applying the relationships of tasks through DSM to the elemental project structures discussed previously, it is possible to create a dynamically linked design environment. The nature of the environment is described by the following casual loop structure (Figure 9):

1. Initial iteration begins with a quantity of design tasks,
2. Engineers and managers with specific knowledge of their design disciplines must communicate information related to their design tasking to the group in order to provide dependent design tasks with input data,

3. Based on the level of organizational communication (ranging from disconnected to fully integrated design teams) and the imposed design constraints (such as design requirements and design margins), an engineer finds that the initial assumptions made to proceed with the design may or may not be the same at the end of the design iteration
4. As a result of interaction…if communication is lacking or the design is not sufficiently constrained, then the design tasks may be delayed due to competing variations in the initial design assumptions or fail entirely due to coupling with divergent tasks.

The result is a dynamic model with the following hierarchical structure: the complete spiral is a project structure, the tasks flowing within the project structure are themselves project structures represented by the number of nodes in the spiral, and each of these has task flows corresponding to the quantity of subtasks required to perform the task. The rework level is determined by the introduction of an error rate to each task as well as their dependence on errors committed in coupled tasks.

The Model Scheme Applied to the NDP Model

The naval surface combatant (DDG 51) design tasks were examined, aggregated, and applied to the DSM method described above. The matrix is shown in Figure 10 and its resultant network shown in Figure 11. The matrix shows six different design nodes representing the greatest aggregation of engineering disciplines active in the design process. At this level the coupling of tasks is complete and convergence of design would be next to impossible to model. Thus, the next layer, task elements, is added. Task elements represent separation of design disciplines by specific types of tasks performed. At this level we see that many tasks do begin to uncouple, allowing initiation of a convergent process. The model applies a final layer (not shown) that completes the hierarchy of task breakdown into design deliverables (for example weight reports or vulnerability analysis). This final layer captures both interactions among tasks but also the necessity of tasks at different phases of design (i.e. tasks coupled to hullform specification at concept design versus those coupled during detailed design.)

The generic system dynamics project model demonstrated earlier is tailored to incorporate the matrix of design tasks as well as other generators of rework and delays specific to naval design. The resulting model "engine" is shown in Figure 12. The work accomplishment structure demonstrates several important properties. Dependent on the current design phase, baseline tasks are released (release rate) for initial work, worked upon as resources (information and manpower) are available (Assign Rate), and completed based on current productivity (Comp Rate f). Tasks are reworked due to design coupling (Design Spiral Matrix through Design Spiral Rate) and due to errors (Internal Error Rate and Review Error Rate). Coupled tasks are reworked at a rate consistent with the following criteria:

- As task A is completed, a fraction of that task is "undone" by concurrent work in tasks to which task A is dependent
- Task A is "undone" at a rate not to exceed its own completion rate or
- "Undone" at the fastest rate of all its input tasks.

The feedback fraction represents the fraction of tasks that are "undone" by process concurrence. The value may be thought of as either the average allowable margin for change at the given design phase or as 1 minus the fraction of performance and cost lock-in that has occurred at that phase of the design. Tasks are reworked due to errors within the task (Internal Error Rate) and errors generated by coupled information to other tasks (Review Error Rate). Both sets of rework from errors will be heavily dependent on timing and level of QA. The discovery of errors in review will have a greater negative impact than those discovered internally. A key structure in the process is the inclusion of review and approval. As discovered in the DAC analysis, the review process is a source of tremendous cycle time delay and growth. This process cannot be removed, as law requires such review. However, the extent and duration is subject to interpretation. Review is considered an internal activity performed at the program level and below. Primary participants are program management staff, activity staff (both NAVSEA and contractors) and interested parties. Approval is the acceptance of the design by external forces. Approval can include those organizations required to participate by law (DON, DOD and program managers), customers, etc. The final component to the accomplishment structure is the flow of rework back to the process stream.

Those tasks that are sent to iteration must be coordinated to determine what data has changed and what errors must be corrected. The coordination rate is (like the approval and review dynamic) a first order control through the stock of rework (TBCoord). Note that the flow back (Coord Rate) is heavily linked to factors such as speed of information transfer, time available for meetings and communication among design participants and other such communication factors.

Additional Elements of the NDP Model

The accomplishment structure represents the "engine" of the NDP model. However, there are many other components that necessarily impact the design process. Many factors external to the design process for a surface combatant do have tremendous influences. These factors can include Congressional allocation of funds, changing threat capabilities, impacts of other design programs, or disposition of US Naval forces. These factors introduce a level of complexity that the current model does not address. These factors are beyond the boundaries of the stated problem. Impacted process variables such as complexity of specific design tasks (mandays per task), time required to adjust annual funding (years), and pressure to maintain design schedule (days schedule shifted per days behind schedule), are considered exogenous. These factors are used to calibrate the model behavior to meet observations. The endogenous structure of the design process model captures six key aspects:

- Financial resources
- Manpower resources
- Allocation and productivity of manpower
- Schedule adherence
- Error generation and flow
- Accomplishment structure

Financial resources represent the Planning, Programming, and Budgeting (PPBS) interface with the design process. Time delays between request and allocations, particularly with respect to calendar driven timing of requests, are the most notable features of this dynamic sector. Manpower resources are the accumulation of design talent, both government and private sector, which expend financial resources as necessary to develop design products. Key dynamic forces for manpower are budget constraints, talent pools, learning curves for design experience, and fluctuations between government and private participation during different design phases. Allocation and productivity of manpower captures the actual rates of design development achieved by available resources. Productivity is influenced by the dynamics of overtime and fatigue, learning curves, effectiveness of teaming, and productive (design) vice non-productive (administration and QA) activities. Schedule adherence monitors the impacts of setting and maintaining the process schedule. Schedule dynamics include schedule slip relative to perceived productivity and perceived progress, and schedule slip relative to levels of funding. Error generation and flow refers to the rate of design rework initiated by creation and discovery of design errors. Error dynamics are attributed to timing of error creation and discovery, schedule pressure influences, QA effort levels, and impacts of errors on coupled tasks. These sectors combine with the previously described accomplishment structure to capture the multitude of internal process dynamics observed in naval design

Baseline Results and Sensitivity Analysis

The resultant model generates baseline results as shown in Figure 13. The output demonstrates both the increasing efforts in late design phases and fluctuations within individual phases. Between phases, manpower is increased in correspondence to the number and detail of design tasks being accomplished. For example, 1407 man-months were expended during the 24 month concept design phase compared to over 6700 man-months expended during the 26 month detailed design phase. These efforts correlate to an increase of 720% in total number of design deliverables from the concept phase through detailed design. The level of effort expended to rework vice initial work shows errors at detailed design decreased to levels 25% those at concept design while design changes due to design task coupling increase by over 690% from concept to detailed design. Within phases, many unusual fluctuations occurred. These fluctuations are compared to raw data from the DDG 51 program and used to calibrate the baseline results to produce a more accurate model. For instance, the baseline model does accurately predict a spike of manpower will occur near the end of the preliminary design phase as shown in Figure 14. However, the spike was premature (occurring in March 1983 vice May 1983) and the subsequent ramp up to contract design was too late (September 1983 vice July 1983). The spike is the result of high rework of design options in the review chain. For the actual program, 14 design and procurement options were assembled in response to cost overruns in the estimated total procurement cost of the baseline designs (NSWC Carderock, 1984). The result was a control feedback loop between design effort and estimated design costs. The baseline model review rate was adjusted to capture the correct timing of the spike and the hiring start for contract design was adjusted to demonstrate the rapid turnover to the next design phase following design approval. Similar phase dynamics include the spikes and decays from months 42 through 54 corresponding to timing of fund availability from PPBS and spikes at months 24 and 62 corresponding to milestone approvals.

The calibration of the baseline model demonstrates the ability of system dynamics to capture the majority of system behavior in the adjustment of only a few, high leverage variables. For the case of the current model, two variables dominated the calibration: nominal productivity and feedback fraction. Nominal productivity was determined initially by examining the observed productivity (man-hours expended to deliverables produced) for the DDG 51 program (Naval Sea Systems Command, 1986). The observed productivity values represent the net effect of nominal productivity as well as all factors that influence efforts such as overtime, fatigue, schedule and performance pressures, error rates, etc. When observed productivity is used as nominal, the model results indicate a design timeline compressed by 57% that of the observed schedule. This compression indicates that systemic feedback endogenous to the model accounts for over half the actual productivity effects produced in the process. Reduction of the nominal productivity value by a factor of 43% produces a model that correlates closely with the observed manpower and schedule for the DDG 51 program. The model also demonstrates sensitivity to the variable "feedback fraction". The baseline model assumes a feedback fraction of 50%. By this, it assumes that 50% of information shared by coupled tasks will adversely impact concurrent development efforts resulting in required rework. Sensitivity analysis (see Figure 15) shows that near 50%, the feedback fraction has limited impact on resultant design duration. Varying the feedback fraction between 49% and 51% will proportionally change duration by a mere 0.25%. However, in the region of 45% to 55%, the duration is impacted by over 7.5%. The region of greatest positive returns to scale (RTS) occurs around 39%. The sensitivity of the model to the variables nominal productivity and feedback fraction demonstrates that a successful process improvement effort should seek to optimize these values.

What-If Scenario

From the baseline model, we can examine the impacts of process changes given by the application of a process improvement effort, in this case, IPPD. First, we must define the objective features of IPPD relative to the current process. For application in DOD programs, The National Center for Advanced Technologies (NCAT) (1998) has published an excellent primer on the features of IPPD. From this source, the following generic, objective elements are apparent:

- Design for Affordability: reposition many manufacturing and support related analysis tasks to early design stages
- Early Knowledge of Design Space: examine more design concepts in greater depth during early design stages
- Extend Design Freedom Later in Process: resist selection of single design options until later design stages
- Team/Workgroup Constructs: invoke permanent teaming structure versus continuously reassigning individuals to meet schedule pressures, i.e. crisis management
- Electronic Database and Digital Simulation: implement formal information structure early and manipulate data as possible to simulate complex design tasks in early design stages
- Concurrent Development: compress and couple design schedules to provide greater knowledge of the design in early stages
- Optimized Decision Process: select design options based on objective design attributes rated against an exhaustive, optimized design space

These IPPD elements are best summarized by the following four components: Systems Engineering, Quality Engineering, Top Down Design Decision Support, and Computer Integrated Environment. Systems engineering provides the systematic decomposition of top-level design attributes down to component definitions. Quality engineering is the field of methods providing recomposition of design components to realizable systems. Traditionally, these methods have been implemented in naval design as sequential, "over the wall" design techniques. However, IPPD would seek to develop these fields concurrently. The interface between those engineering techniques is the Top Down Design Decision Support structure supported by a common information structure, or Computer Integrated Environment. In the concurrent environment, information about system level design and component level design would be actively shared and balanced by objective design trade-offs. The impacts of these features on the design model include:

- transfer of late design tasks and their related DSM structures to earlier stages,
- addition of design tasks for information management and increased total designs examined,
- coupling of review flow points to completion of tasks relating to objective decision values,
- improved QA efficiency with automated error detection, and
- increased design coordination rates for information exchange.

There are many additional features that could be included, but these suffice for current process comparison.

To examine the impacts of these process changes, the baseline model is modified. An example of one potential IPPD representation is shown in Figure 16. For this scenario, 10% of all design tasks and their structural linkages have been transferred from the detailed design phase to concept and preliminary design. To compensate for the increased requirements, 10% of resources (funds and available manpower) have been reallocated to the early design stages and the desired time schedule has been increased by 6 months for concept design and decreased by 6 months for detailed design. Average time for coordination of design tasks (information transfer and non-productive meeting overhead) has decreased by 10%. With increased participation and design understanding inherent with IPPD, the model assumes a 10% decrease in review and approval time. The results demonstrate both expected gains and unforeseen consequences. First, net manpower costs have risen by 255% for concept design, but decreased by 79% in preliminary and contract design and by over 40% in detailed design. The result is an overall decrease in design costs by 33%. Total cycle time has decreased by 24%. In particular, detailed design has compressed to 45% the duration of the baseline model. However, the 33% increase in scheduled duration for concept design was not sufficient to meet required design time. The resultant concept design phase is extended by 20.8% over the desired 24-month duration. Also, note that early design tasks still reflect a ramp usage of manpower vice the step increase advocated by the teaming structure of IPPD. This corresponds to the fact that specific initial tasks, such as requirements setting, must be completed before sufficient information is generated to support specific detailed tasks, such as producibility assessment or manning. The model realizes the primary features of IPPD, high levels of early design change negating need for changes during detailed design. Specifically, net design changes (measured as rework of tasks) are increased by over 40% from the baseline at the concept design level. To the contrary, all later design stages see decreased levels of change relative to the baseline culminating in an 80% decrease in design changes at the detailed design stage.

These systemic impacts demonstrate the potential leverage of IPPD policies over traditional design process methodology. However, the demonstration has been applied in a holistic manner…funding, schedule, requirements, etc have been modified to "game" the system. What if funding or schedule had not been reasonably adjusted? For example, if planned annual funding is not increased by 10% for concept design, then the model suggests that the concept design phase and subsequent phases are extended by 5 to 6 months. Also, actual funds spent will approach the proposed 10% increased funding levels due to the extended time. If realistic adjustments to proposed schedule are not included in the process improvement implementation, such as increased duration of concept design, then other negative effects result. Specifically, the overall cycle time does realize a compression of about 22%, similar to the results noted earlier. However, concept design still takes over 24 months to perform (vice 18) and design rework in all design phases increases by over 10% that shown for the holistic IPPD example. As such, productive activity (such as exploring alternative design concepts) is lost in favor of error generated rework caused in the attempt to maintain a condensed schedule that is never realized at the concept level.

What if the advertised improvements of IPPD themselves are not fully realized? Specifically, suppose the error rate from baseline methods is reduced by 5% vice 10%. In this case, the cycle time is unchanged and design rework increases by a modest 3%. This indicates that the schedule of the IPPD implementation relative to the current model is not sensitive to error rate. Relating to the previous discussion of feedback fraction as a sensitivity variable, suppose that the IPPD methodology causes the feedback fraction to increase by 3% due to the increased demand for design iterations and design interactions among concurrent activities. In this case, the design duration increases by 8% relative to the IPPD example. However, the most adverse feature is the transition of peak levels of design changes from concept to preliminary design with a corresponding increase in manpower effort of 145%. This is reflective of the greater coupling of tasks in preliminary design stages and later versus that of concept design. It happened that the transition of late design tasks to early stages as prescribed by this scenario, created the coupling effect previously compensated by the reduced feedback fraction. The potential sensitivities and systemic influences of a single process improvement initiative can produce a variety of effects both desired and not.

Conclusions

Traditional process analysis tools provide the ability to capture hard process variables such as design concurrence or phase duration. These operationally based methods attempt to capture the dominant systemic influences (human factors, error propagation and design feedback) as a correlation of statistically behavior. Thus, those models may not accurately capture changes that effect the dynamic relationships of those behaviors, as relevant statistical data will likely not be available. To the contrary, system dynamics modeling provides a means to assess process improvements that must incorporate both architectural changes to the process and the influences of non-linear responses such as convergent iteration of design tasks. To this end, the NDP model demonstrates the potential usage of system dynamics to analyze a complex improvement effort and understand both positive and negative outcomes. Whereas traditional process analysis methods provide a wealth of operational process improvements such as statistical process control (SPC), system dynamics modeling can reveal sensitivity of policy options and strategic leverage as regards the trade of cost, schedule and performance. However, system dynamics modeling is not intended for daily operational management of a project. To this end, EVM and Gantt Charts are very applicable.

The NDP model demonstrates the power of system modeling as a method to perform "business wargaming." This particular model, as tailored to a ship program that started over 20 years ago, builds not on specific sets of data, but on the common sense and physical structures observable in all naval design projects. This is the true strength of the modeling. By building on recognized and agreed upon process structures, such as the flow lanes for design tasks or the process for establishing and shifting schedule, the model can be applied to other naval projects. Specifically, the generic structure of the naval ship design model reflects the policy and process mechanisms contained in the ship design process and could ultimately be applied to current efforts such as the DD 21 or NSSN programs. No doubt, such programs could benefit from the knowledge gained in optimizing IPPD or TQM within those efforts. However, the greatest benefit from such modeling is not found in the resultant scenarios. Rather, knowledge is gained by the learning associated with model building and understanding the mechanisms in a process that lead to optimal implementation of process improvement. For instance, the current model does not address explicitly the issues of ship manufacturing or the macro influences of competing design efforts in the DON and DOD. Every potential question from a program manager or process observer, must be examined fully (by the system dynamics steps) in order to implement a useful solution. However, strategically based models, such as the NDP model, can provide a common mental model from which to study broader acquisition questions.

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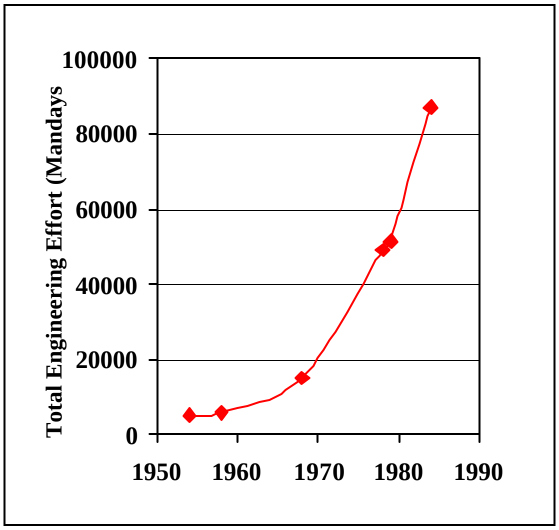

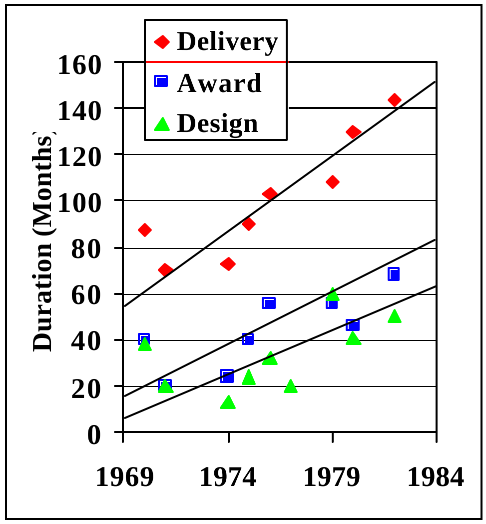

Figure 1 Combatant Cycle Time Trends (Ryan and Jons, 1991)

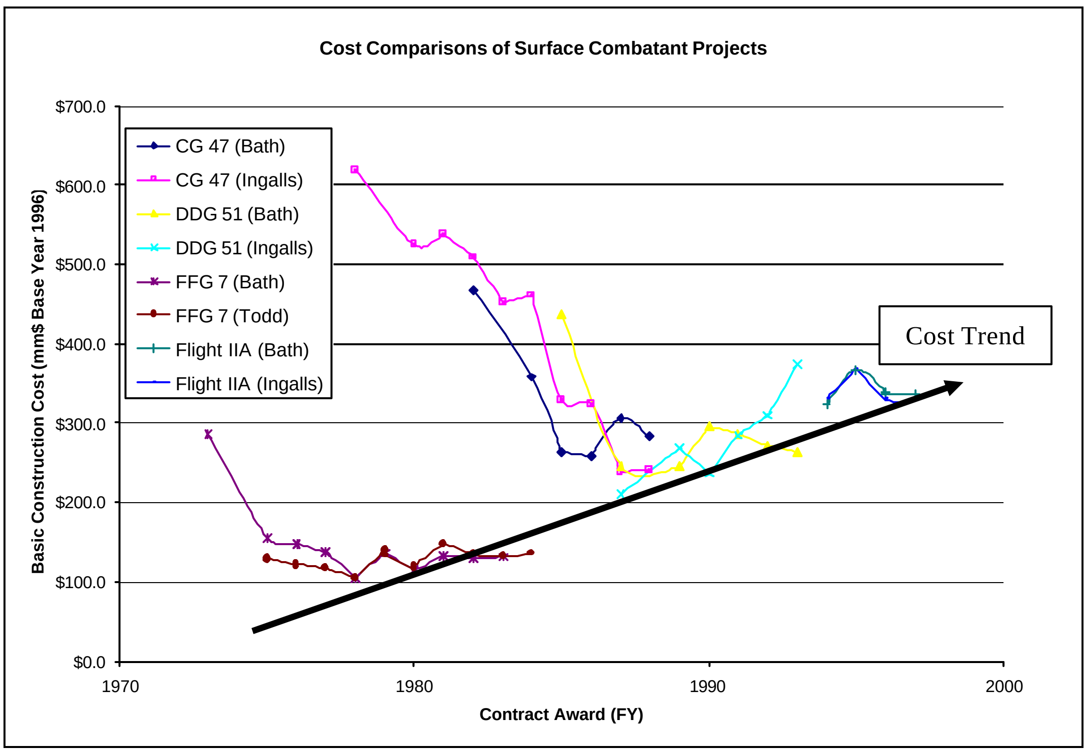

Figure 2 Basic Cost of Construction Trends for Surface Combatants (Colton, 1997)

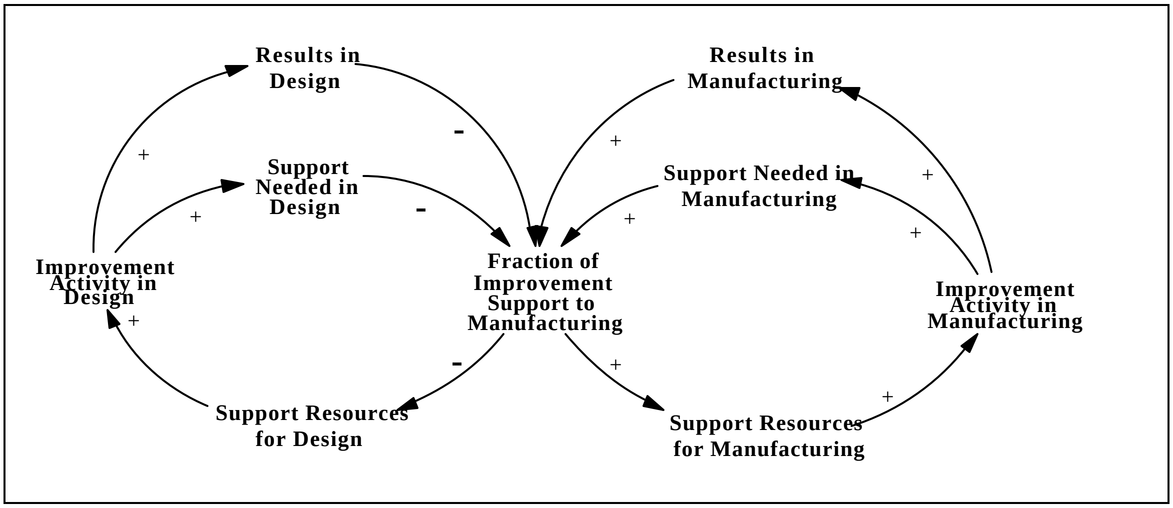

Figure 3 Competing Resources in Process Improvement

Technique/Tool	Purpose
Work Breakdown Structure (WBS)	Basic definition of the project work. Precedes the project schedule and cost estimates
Gantt Charts	Representation of project schedule, may show simple precedence relationships
Project Network Techniques: PERT, CPM, PDM, GERT	Analysis of scheduling impacts based on precedence relationships, cost estimation, resource allocation, management and risk analysis, and input-output relationships

Table 1 Traditional Project Management Techiques (Rodrigues and Bowers, 1996)

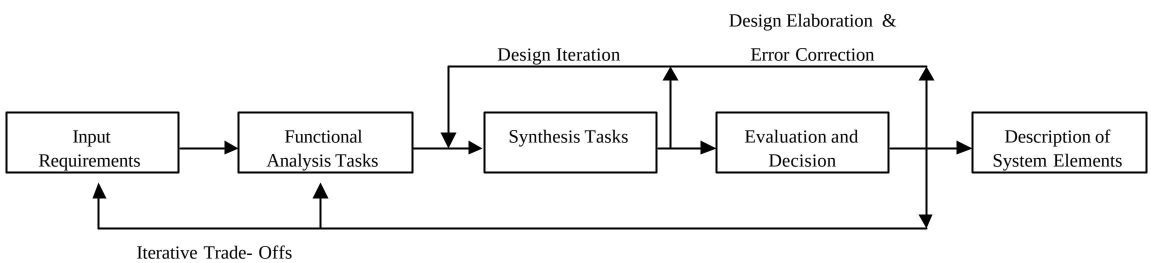

Figure 4 Systems Engineering Process (Kockler, Withers, Poodiack and Gierman, 1990)

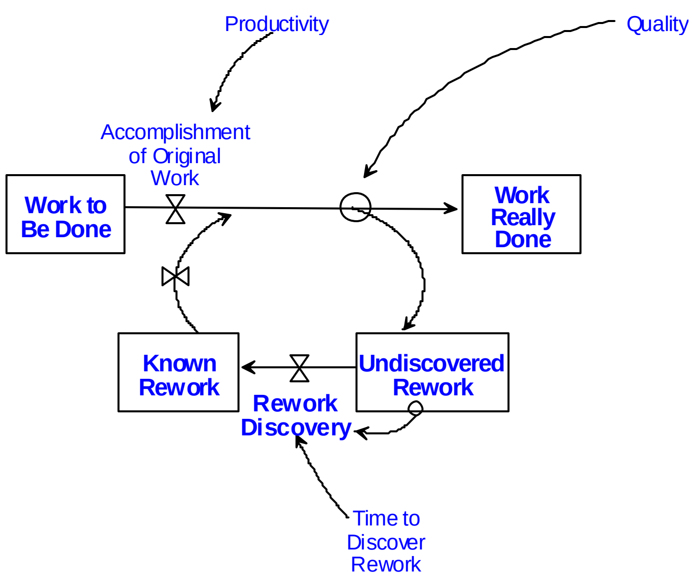

Figure 5 Generic System Dynamics Project Structure (Lyneis, 1998)

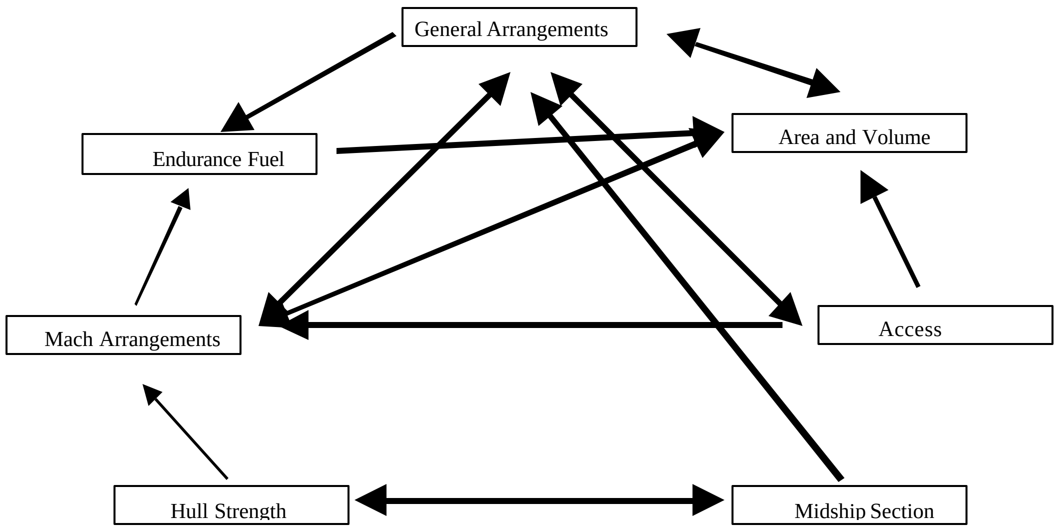

Figure 6 Simple Iterative Design Network

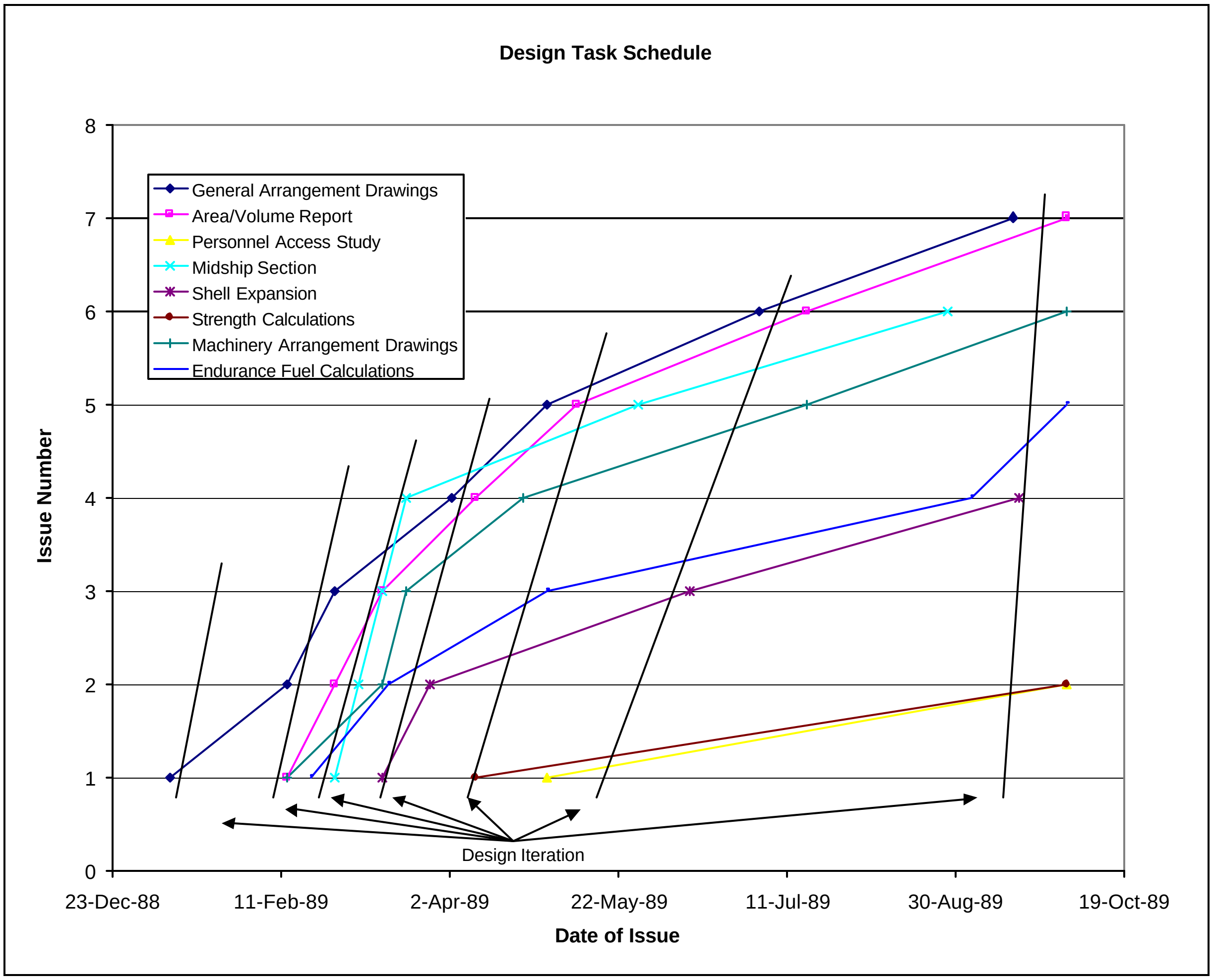

Figure 7 Sample Design Schedule Estimates in a Naval Design (NAVSEA, 1987)

		1	2	3	4	5	6	7
General Arrangement Drawings	1	0	1	1	0	0	1	1
Area/Volume Report	2	1	0	0	0	0	1	1
Personnel Access Study	3	1	1	0	0	0	1	0
Midship Section	4	1	0	0	0	1	0	0
Strength Calculations	5	0	0	0	1	0	0	0
Machinery Arrangement Drawings	6	1	1	0	0	0	0	1
Endurance Fuel Calculations	7	0	1	0	0	0	1	0

Figure 8 DSM for Sample Design Tasks

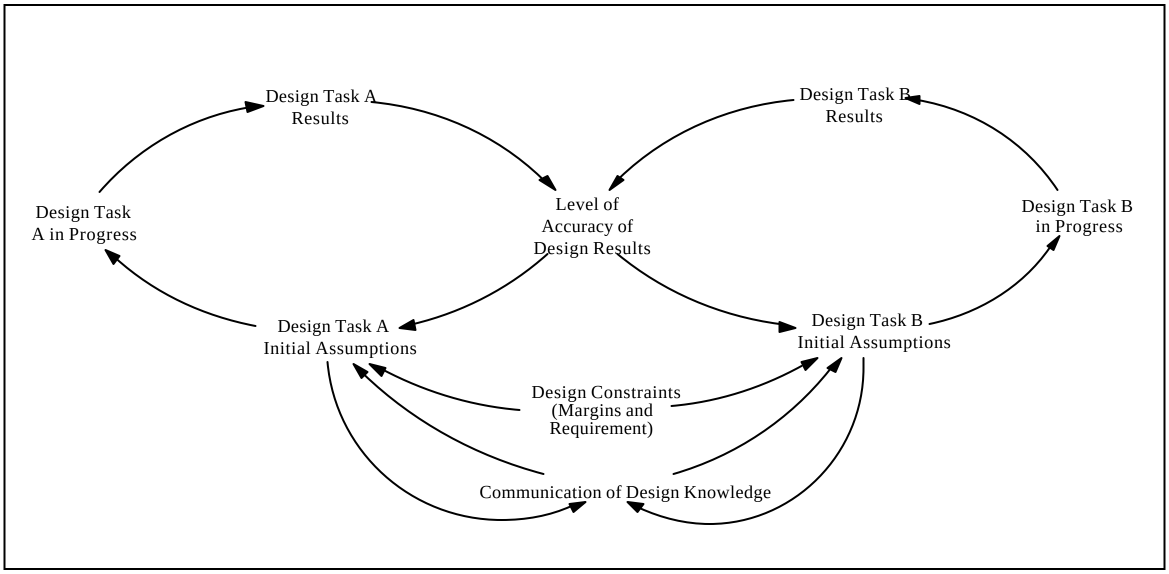

Figure 9 Generic Design Task Relationship

Node	Task Element	Node	Task	A 1	A 2	A 3	B 1	B 2	B 3	B 4	B 5	C 1	C 2	C 3	C 4	C 5	C 6	C 7	D 1	D 2	D 3	D 4	D 5	E 1	E 2	F 1
Programatic	Program Management Tasks	A	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
	Requirements & Assessment	A	2	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
	Risk Mitigation & Coordination	A	3	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Systems Engineering	Logistics and Reliability Engineering	B	1	1	1	1	0	1	0	0	1	0	0	0	0	1	1	1	1	1	1	1	1	1	1	0
	Design Integration & Specifications	B	2	1	1	1	0	0	1	0	1	1	1	0	0	1	1	1	1	1	1	1	1	1	1	0
	Producibility and Production Engineering	B	3	1	1	1	1	1	0	0	0	1	1	0	0	1	1	1	1	1	1	1	1	1	1	0
	Performance-Requirements Assessment	B	4	1	1	0	1	0	0	0	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	0
	Manning	B	5	1	1	1	0	0	0	1	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	0
Hull Engineering	Hull Geometry	C	1	1	1	1	0	0	0	1	0	0	1	1	1	1	0	1	1	1	1	1	1	1	1	1
	Weight, Hull Subdivision & Hydrostatic Design	C	2	1	1	0	0	0	0	1	0	1	0	0	1	1	1	1	1	1	1	1	1	1	1	1
	Hydrodynamics-Resistance	C	3	1	1	0	0	0	0	0	0	1	0	0	0	1	0	0	0	1	0	0	0	0	1	0
	Hydrodynamics-Seakeeping	C	4	1	1	0	0	0	0	0	0	1	1	1	0	1	0	0	0	0	0	1	0	0	0	0
	Hydrodynamics-Maneuvering, Appendage & Propeller Design	C	5	1	1	1	0	0	0	1	0	1	1	0	1	0	0	0	0	1	0	1	0	0	0	0
	Structures-Static and Dynamic Design	C	6	1	1	1	0	0	0	1	0	1	1	0	1	1	0	1	1	1	1	1	1	1	1	1
	Space and Arrangements	C	7	1	1	0	0	0	0	1	1	1	1	0	0	1	1	0	1	1	1	1	1	1	1	1
Machinery Systems Engineering	Machinery Systems Design and Integration	D	1	1	1	1	0	0	0	1	1	1	1	1	0	1	0	1	0	1	1	1	1	1	1	1
	Propulsion Systems	D	2	1	1	1	0	0	0	1	0	1	1	1	0	1	0	1	1	0	1	1	0	0	0	1
	Electrical Systems	D	3	1	1	1	0	0	0	1	1	1	1	0	0	1	0	1	1	1	0	1	1	1	1	1
	Auxiliary and Support Systems	D	4	1	1	1	0	0	0	1	1	1	1	0	0	1	0	1	1	1	1	0	1	1	1	1
	Deck, Handling and Aircraft Support Systems	D	5	1	1	1	0	0	0	1	0	0	1	0	1	0	0	1	1	0	1	1	0	0	0	1
Mission Systems Engineering	Mission Systems Selection, Design and Integration	E	1	1	1	1	0	0	0	1	0	0	1	0	1	0	0	1	0	0	1	1	0	0	1	1
	Topside Design and Integration	E	2	1	1	1	0	0	0	1	0	0	1	0	0	0	0	1	0	0	1	1	0	1	0	1
Cost	Cost Estimates & Analysis	F	1	1	1	1	0	0	1	0	1	1	1	0	0	1	1	1	1	1	1	1	1	1	1	0

Figure 10 NDPM Task Interaction Matrix

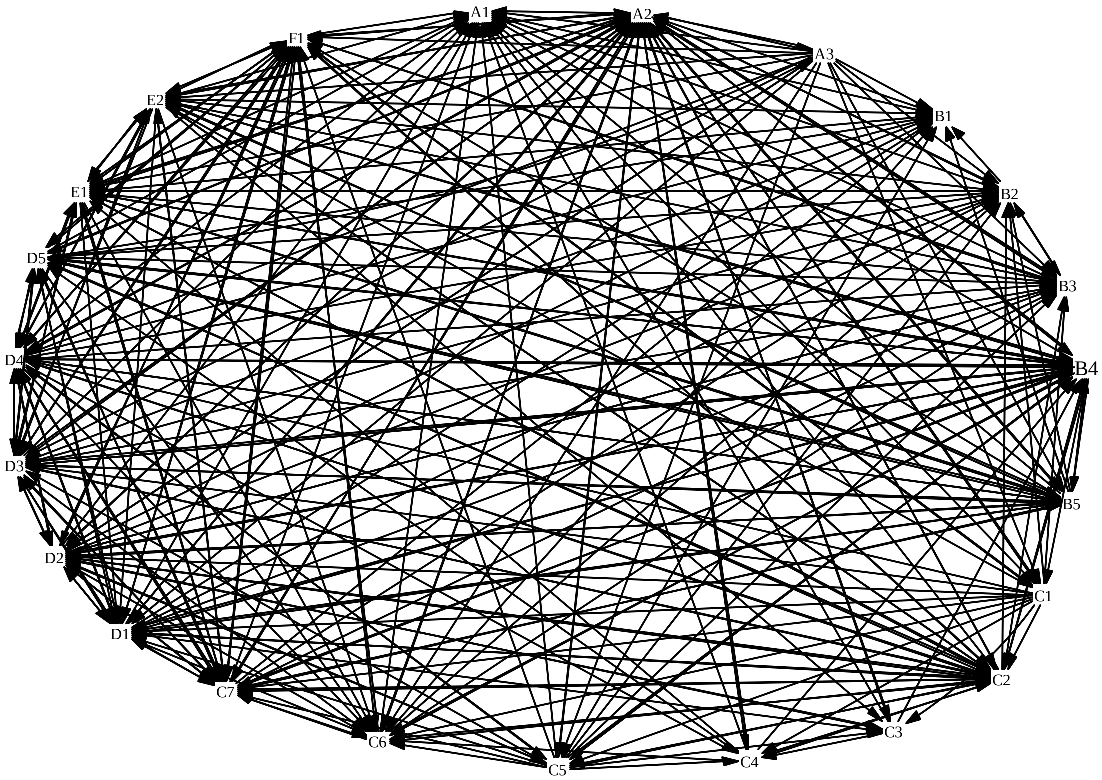

Figure 11 Graphical Representation of DSM for NDPM

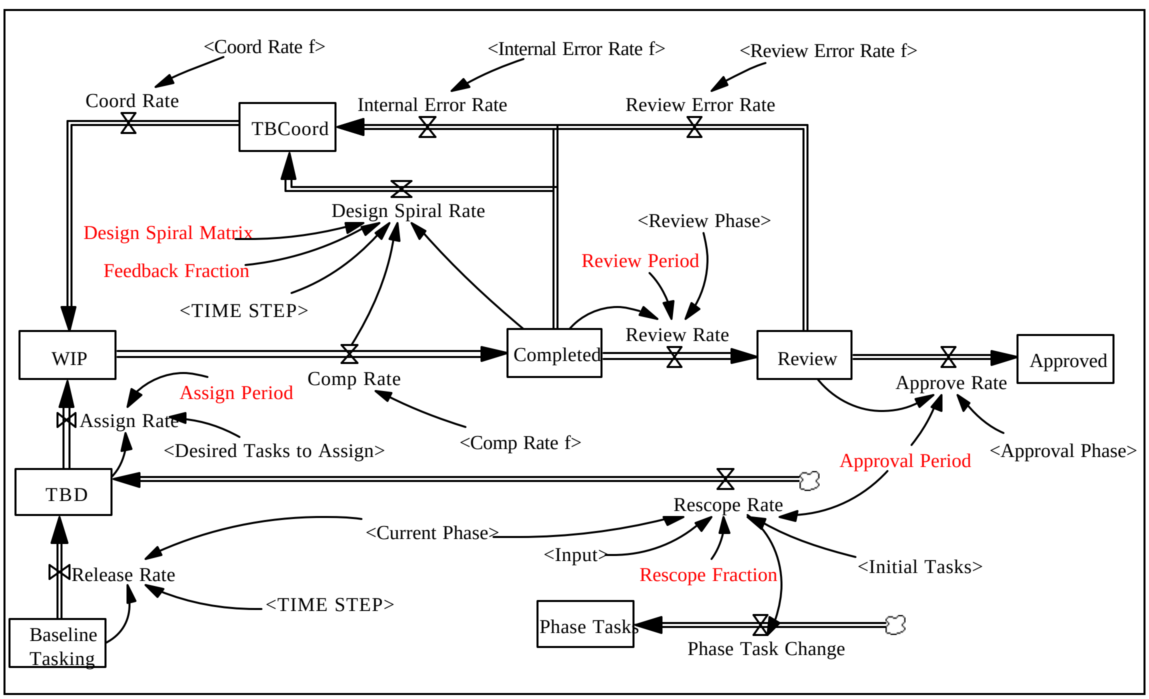

Figure 12 Naval Design Process Model Task Accomplishment Structure

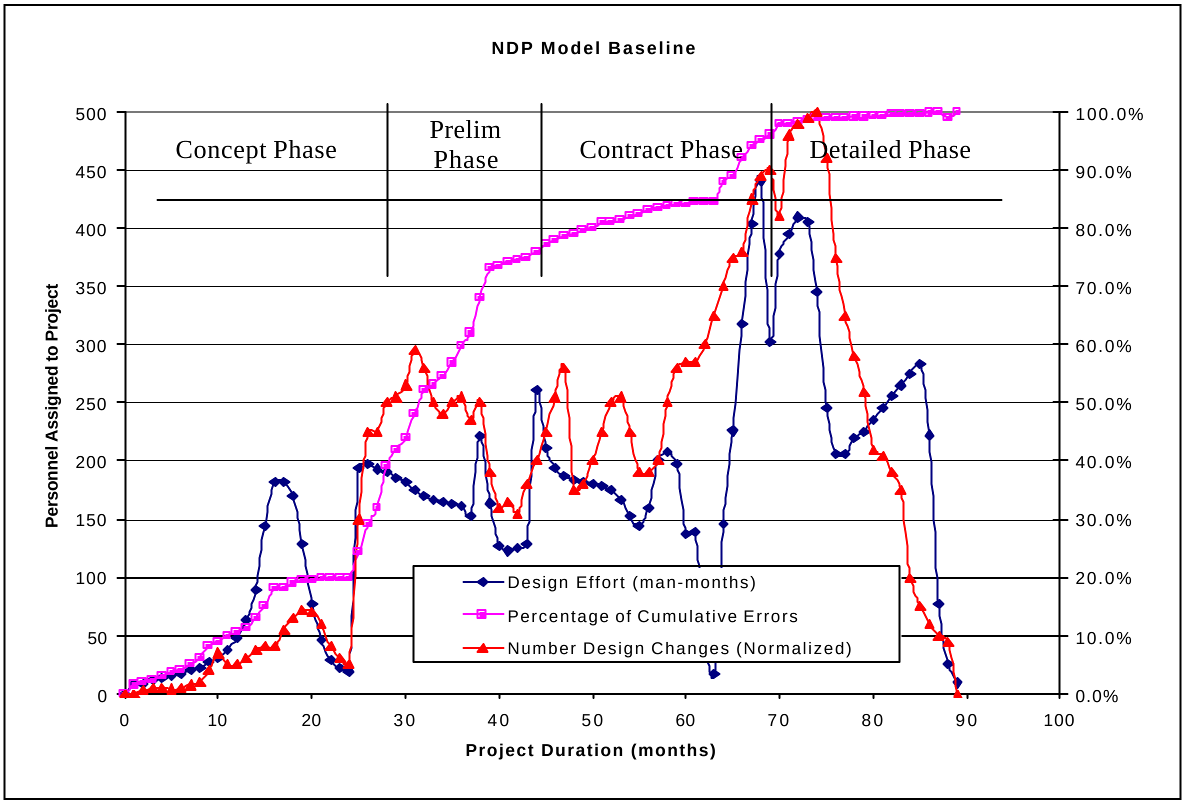

Figure 13 Baseline Results from the Naval Design Process Model

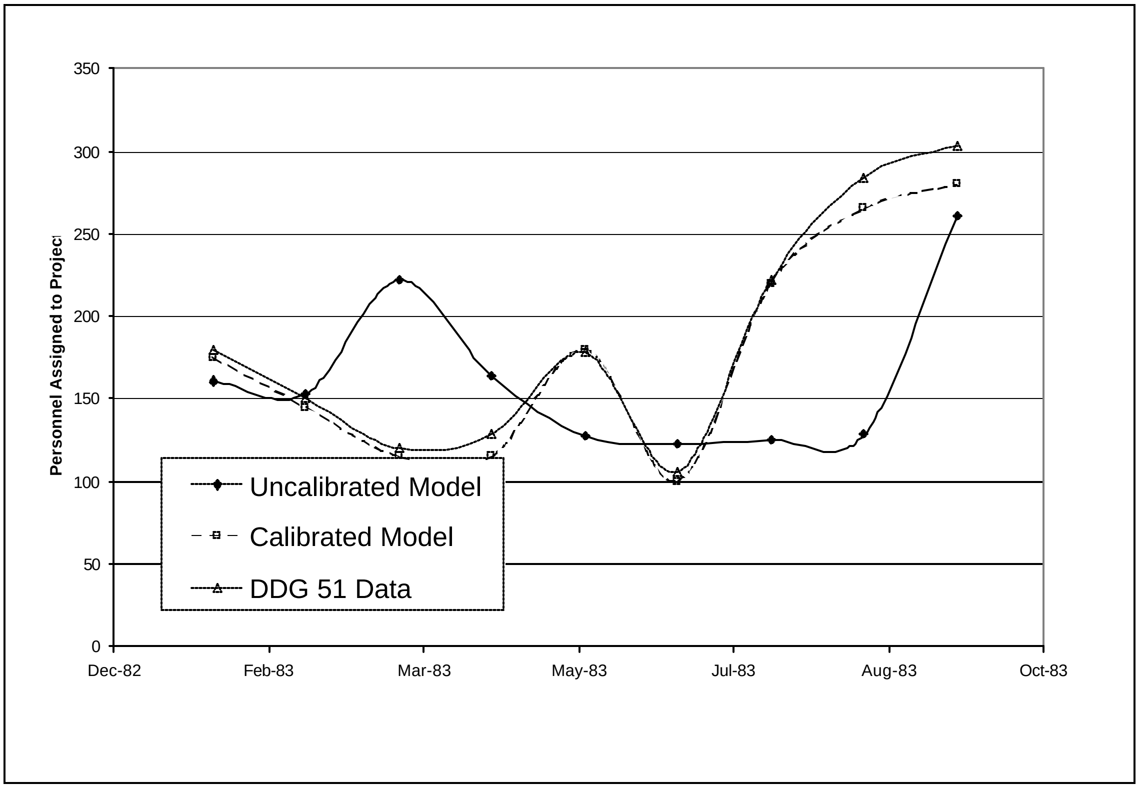

Figure 14 Model Calibration and DDG 51 Data for Preliminary Design Completion

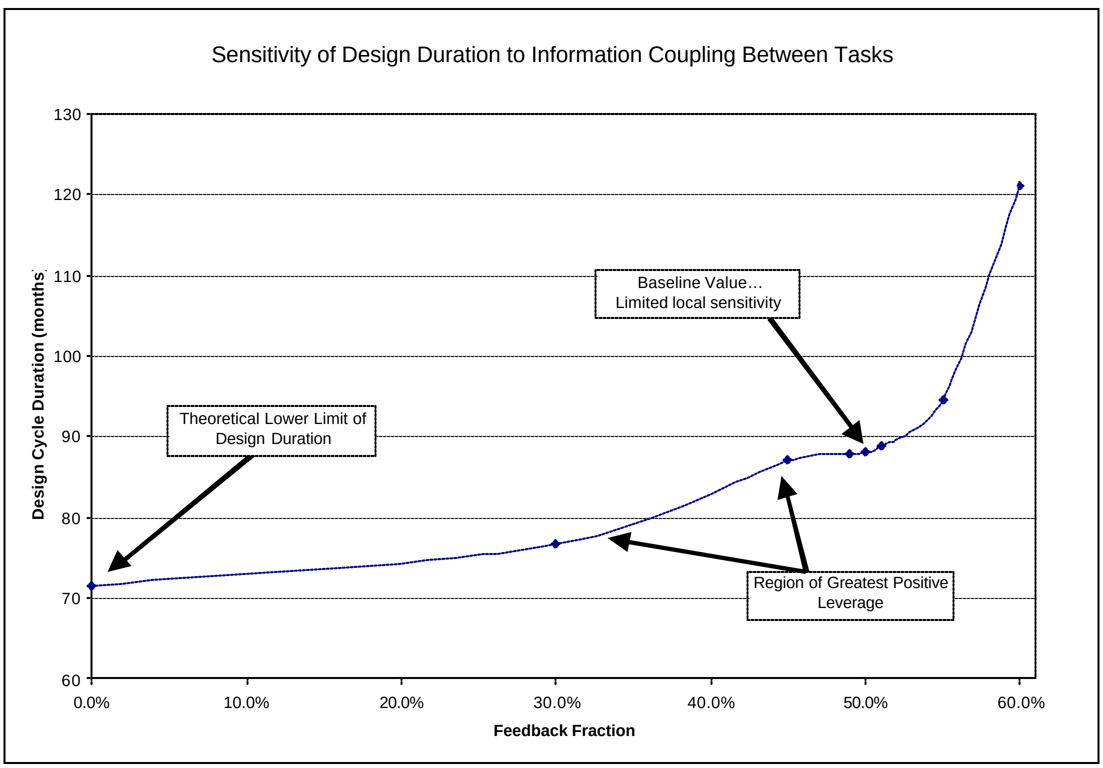

Figure 15 Sensitivi ty of Design Duration to Design Feedback

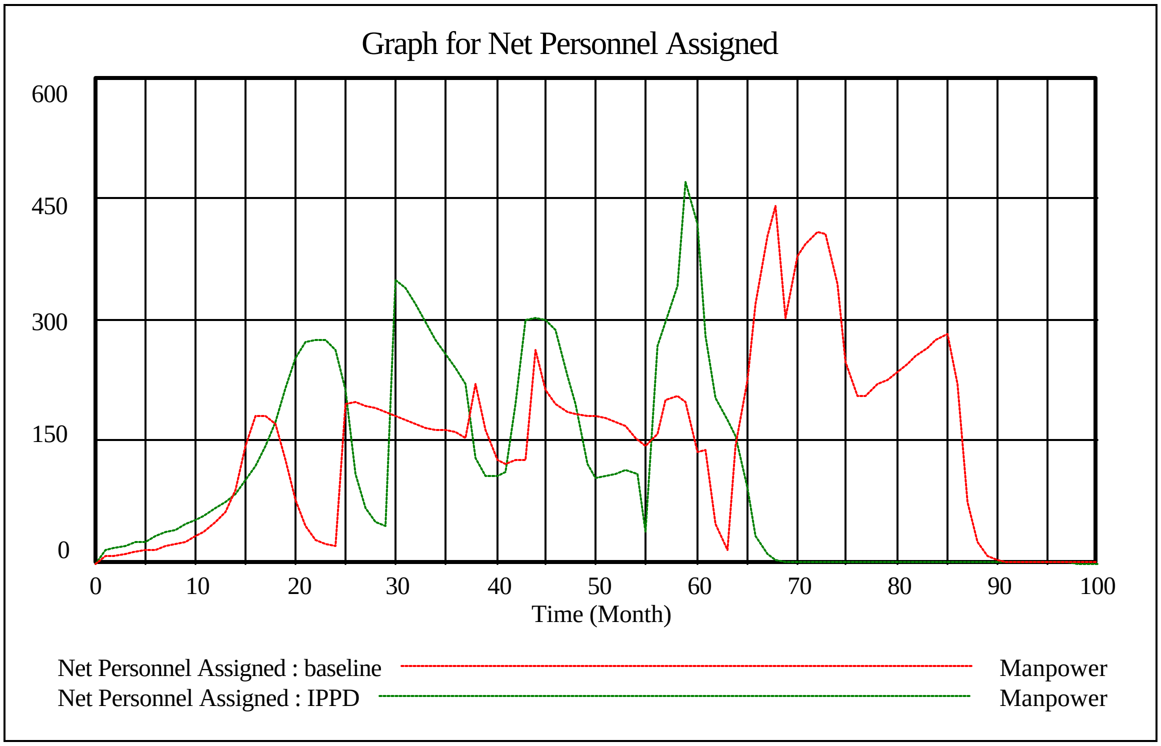

Figure 16 IPPD Scenario vs. Baseline