REENGINEERING SPACE PROJECTS

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Introduction

In an era of shrinking funds for space exploration, JPL is undergoing a significant reengineering effort designed to reduce costs of flight projects by 33 percent, and time to launch by 50 percent. It has been projected that the laboratories business base of 450 million annually for Flight projects can be reduced by 115 million. It is expected that the new processes will be deployed by 1998.

Following the lead of Dr. Michael Hammer, coauthor of 'Reengineering the Corporation', JPL is transforming a vertical organization into a agile, flat organization of coordinated engineering processes. It is the design of these concurrent processes, with an integrated set of new tools, that enable the savings projected above.

The paper describes the four major processes being used at the laboratory and their relationships to each other. The focus of the technical material is on the design and specifications aspects of new projects. It describes how new design tools can be integrated for space applications to reduce the design cycle time, and link a verified design to an automated manufacturing process. Most of these new tools are commercial off the self (COTS) tools, so no new developments are required, only new ways of utilizing the information to promote high concurrence.

The new tools are featured for a new process that eliminates the need for the traditional serial requirements process. Substituting for the levels of requirements is a modeling capability providing an executable specification, i.e., a functional specification that can be executed over time to describe all of the states of an interface, not just a worst case. These 'systems models' prevent over design for missions requiring tight margins, as most of the NASA's future mission set dots. The models also relate to a requirements document tool for supporting information. A model based system of requirements is more agile and versatile with regard to proposed changes. Evaluations with regard risk and cost implications to mission changes are now easy, and do not impede progress.

This model set, representing the systems requirements, is related to a subsystem design requirements process that can be directly linked to hardware and software for automatic manufacturing. Subsystem models are based on the behavior model concept now being used in the commercial electronics industry. The behavior models can be simulated together in a flight system testbed. This simulation is exercised with a typical flight scenario, and the results compared to the systems models. The overall system is processed based, so after verification manufacturing, assembly, and test can take place in an automated fashion from the behavior models.

Finally, the paper concludes with a description of the engineering pilots ongoing at JPL. Each pilot was selected to develop the modeling capabilities of each of the four processes, and to shake out the new engineering approach. 1 mmediate results have alread y been realized by employing these techniques to studies in the Project Design Center, PDC.

Business Case

Recently, an important survey was conducted by the US Navy. The survey was part of the Joint Strike Fighter Program aimed at the Manufacturing Affordability Development Program.(Reference 1). The survey produced some amazing results which apply to the problem of reengineering the Aerospace industrial complex. Figure 1 was produced from a survey of seventeen Aerospace Facilities. 1(shows the improvement learning curve, using existing designs, but with improved products techniques anti better control at each production stage. However, if one fundamentally changes the PROCESS, a shift in the ordinate occurs even for a single production unit. This is precisely the case for single scientific missions. Note, the ordinate shift is on the order of 25-30 percent.

The hope then, is an expected savings of at least 25 percent for single items and more if one can capitalize on the initial design. For JPL, the 1996 flight project business base was about 450 million. All the missions were uniquely design, i.e., each spacecraft was not from a common design, but had inheritance at the subsystem level from a different lineage.

In other words, each falls in the category of a single production unit. If the fundamental process can be changed, the expected savings should be about 25 percent. It would be much less by just improving in the building blocks, and providing more effective control.

Based on an optimistic declining budget prediction, approximately 400 million per annum business is expected in the fourth year. An investment of 20 million per year, for three years, discounted at 5 percent would yield a predicted benefit to cost ratio of 1.4 in the first year. More importantly, these kinds of savings are necessary just to keep a viable space effort should the decline be much greater.

Vertical Structure of Aerospace Industry

The work of Dr. Michael Hammer (Reference 2, 3) has had a profound influence over the reengineering efforts at JPL. He recognizes that corporations have traditionally invested heavily into improving performance of individual tasks. In case after case, corporations moved into automation and robotics to improve production. Many cam to the realization that performance still suffered, and the expectations were not achieved. Hammer points out that the real productivity achievements come when you reengineer the whole process containing the tasks. Its the task handovers, for example, that limit the performance achievements, and those are in need for as much attention as the tasks themselves.

Secondly, he makes the point that only a very small percentage of the work is value added. In corporate America, he estimates that less than one percent of the effort is value added, the rest is overhead charged to the customer.

Also, Hammer makes another observation that is very important to any reengineering effort. Corporations are organized vertically with the belief system that nobody at a lower level can be trusted. In fact, the only way to ensure efficiency is to exercise absolute control over each sub organization. And, when things slip, act quickly with, yet more control. Sometimes, this is clone by inserting more layers into the vertical organization, further separating the upper leadership from the real production people.

It is not surprising that the current engineering approach to design and development mirrors the vertical organization (Reference 4). Projects become preoccupied with requirements process, both the generation process and the subsequent verification (Reference S). Therefore, systems engineering is all about control through requirements. The more complexity, the more requirements, until the designer is overwhelmed with meaningless paper. He usually must correlate the requirements on his own subsystem over several documents.

Attention to the requirements comes from the core belief system of fear of failure and its partner, control. in this paradigm, completeness is the watch word, not performance. over specification is (he expected Norm of such a process. Allocation of margins is the only recourse, not engineering of margins. And the system usually collapses under its own weight, and is largely ignored by the value added people, until testing points out major discrepancies. These two inevitable results is enough to completely discard this relic. What's the alternative? Fortunately, there is an alternative with the advent of the modern " computer technology and real advances in simulation techniques.

<u>Process Engineering</u>

In 1994, JPL engineers recognized the need to improve costs and reduce cycle time for our missions. At the time, the popular idea centered around concurrent engineering. JPL (See Reference 6) built a facility called the PDC, the Product Design Center. Within these facilities, concurrent engineering was to take place, using common tools. In addition, after another popular idea, a test bed for early prototyping was established. However, cycle time did not drop appreciably, although this approach did provide a much needed supporting structure.

A careful examination uncovered that JPL still exercised the old processes, defined out of the sixties, i.e., requirements driven, but improved. After all, it worked for Voyager. What's wrong with these paradigm? Well, its basically sequential, so how can concurrent engineering work with a sequential process? Also, because the organization at JPL had matured, each subsystem had evolved to eliminate the costly handovers, becoming independent of each other. So they resented the collocation now, claiming the increased communications didn't help much. Independence produced duplication of tools, and stimulated heated power struggles over who is better' equipped to do that job after all.

The PDC effort also ignored process. Process engineering began with the idea of adding a permanent team to the PDC, which executes a standard process for all [he flight Projects during the Proposal stage. This process was needed the most, because the demands for quality engineering for new proposal support far exceeded the personnel available. JP1, produced over fifty proposals during 1996, at a savings of 160K per proposal. This amounts to about 8 million dollars savings, or a production increase amounting to twice the number of proposals produced for the same amount of money spent the year before.

JPL's director aggressively moved out with declaration to move to an all process oriented laboratory, and established a reengineering team, called Develop New Products. This team does the process reengineering at JPL, and it is these results which is the main theme of the paper.

Aerospace Culture

It is very important when trying to bring about change within any organization that you examine the culture of the place receiving your communication. At Caltech, and JPL, individuality is the most important part of our Image. The Image has a strong element 'We can do it better . . . and we let everyone know about it.' Then, we remind them if they forget. It is our culture, or image that found work 'arounds' amidst a broken anti dysfunctional process. In other words, we survived the imposed process with sheer ingenuity. There is some aspect of this culture in every Aerospace company in America. It may be an American culture, but Caltech is the epitome.

Of the engineers at JPL, the workers embraced the new concepts, but resisted the loss of individualism. However, the price to pay is continued self sacrifice as costs reductions become more acute. So they are giving ground. Now, we know the upper management is supportive, with the announcement of JPL's declaration. So, where does the other resistance emanate? Its the Project managers at JPL who are still driven by the core issues, anti the middle management who see the organization collapsing into a horizontal or flat form.

Of these, the Project Manager type at JPL is the most confronted. He is faced with the apparent loss of control. After all, he is handed a JPL process to implement, not one of his own choosing. There is the apparent loss of individualism and suffers the illusion Of diminished image. At JPL, the Project Manager used to be autonomous. Again, this theme is true throughout Aerospace America. Its not bad, just a relic of the past, that no longer serves the enterprise system.

Concurrent Horizontal Engineering

We have talked about the vertical structure, and the need for a flatter organization. in particular, we see that the engineering process is a mirror of the organization. What would the engineering process look like with true concurrent processes? At MIT, the lean enterprise approach is a 'team of teams.' At JPL, we have embraced this concept, and the common data base.

Very simply, we have taken advantage of the computational capabilities of COTS tools and formed a 'team of teams' who develop models which communicate through a common data base. It is these models and their interaction that form the foundation of the new third generation approach to Project Engineering (Reference 7). The model environment eliminates over specification, establishes real concurrent communication, and links early prototyping to actual testing of the flight hardware. Continuous verification of the design is now possible through this approach and reduces the Systems Integration test time at the end by a factor of two.

There are no managers below the Project Manager, only value added engineers. Traditional subsystem people are doing systems jobs. The traditional role of the system engineer is changed from a control enforcer, to developing the interfaces between system level models and subsystem models. They also play a strong role in the verification process, especially interfacing the subsystem models to the testbed and other verification labs.

Figure 2 shows the key model developments in this collection. It shows how system cross cutting models interface with the subsystem models. At JPL, the subsystem models are called Behavior models. Characterist ics of this model are such that we can get to hardware anti software almost automatically through CAD tools. Figure 2 implies an increasing fidelity as the subsystems mature. At various stages or builds, system verification occurs in the flight system testbed.

<u>Model Based Development</u>

The heart and sole of the third generation development process is a model based engineering design, not a requirements based system. Figure 3 represents a diagram of these four models, and the relationships between them. There are three kinds of models at this juncture. The first kind are requirements models. These models have been called 'cross cutting'.

The second kinds of models are the engineering design models. JPL and other companies have a large repertoire of these models, and as the computational capability increases, the model fidelity increases. Third are design capture models, and they come in two flavors. The first is what we call 'behavioral models', and the second are the CAD models at the detailed design level. The Boeing company is purported to have first used a behavior model concept with their subcontractor, Honeywell, for the flight deck of the 777. The CAD models have been around for some time, but they were not linked to any design process. The behavior models enable this linking. The fourth kind of models are those used for design verification. The testbed itself is for system verification. Visualization of a encounter geometry is a verification model. These distinctions are important since they relate to a design process. It is interesting to note people lose these distinctions, because they are not process oriented, but product trained.

A behavior model describes the state changes of the subsystem, its interfaces, and components. This model leads to executable specifications. Figure 4 shows an RFS/Instrument 1/0 implementation within a C&DH subsystem. A large subsystem like this may have nested behavior models, where only the nested models are can be directly linked to the CAD tools. The constraint on these lower level models is that given a target technology like a FPGA, CAD tools are available to automatically generate the circuit design.

in Figure 4, the behavior models relate to each other through a common parameters data base. At JPL we use Oracle. Engineering data is stored in the data base, together with limits of the design. Each subsystem engineer is responsible for the update of his design. If the design limits are exceeded, then the system is again balanced to achieve parity of the design margins. This step is important. It eliminates the penalties a subsystems often incur when initial assumptions become invalidated. For large developments this kind of system adjustment was not possible, because of the allocation approach and the lack of visibility, until very late in the development. The requirements process itself becomes a quagmire, and cannot support the kind of rapid change called for in today's missions.

Major Components

There are five key processes at JPL: PPIC, Project Planning, Implementation, Closing; MSD, Mission & System Design; DBAT, Design, Build, Assemble, Test; and VIVO, Validate, Integrate, Verify, Operate. Figure 5 depicts these processes running concurrently (Reference 8). The four process do truly operate in parallel within one third the cost and half the schedule.

All of the processes require an active stockpile, or 'just in time parts'. They also require a commitment from the institution to support a strategic tool set, and support an active improvement system to all the processes. Within this environment, process flourishes, and performance increases.

The processes function in terms of three worlds. Figure 6 depicts: a virtual design world of models, a testbed world for verification, and the real flight world where validation occurs. Figure 5 shows these three processes, MSD, DBAT, and VIVO. MSD is the design space, DBAT is the Build and Test space, and VIVO is represented by the Testbed.

In the following description, wc take each of the three processes, and describe the activities, especially with regard creating the virtual world of related models. The first of these if the MSD process which spans the time frame from proposal to systems test. When wc now say systems test, wc arc referring to the very last series of tests, which do environmental qualification and operations verification. The VIVO process itself is a continuous testing philosophy.

M SD

As indicated above, the most profound changes are the system design process. Figure 7 shows the very eliminatory steps in the early stages of the systems design process. The process begins with science objectives (level 1 requirements), and then proceeds to a standing team of subsystem experts (DBAT people), known as Team X, who hold sessions at the Project Design center, PDC. 'I'cam X performs the iteration, finally generating a design which meets both performance and cost. In doing so, the final design is captured as requirements in a spread sheet system designed by Aerospace corporat ion. The engineering design parameters are then dumped into the oracle data base for the next phase of development. This is an over simplification of the process, but these are the essential steps. PTM stands for Project Trades Models for projects which can enter Team X with a more sophisticated design.

The Aerospace model includes cost as a parameter. Costing data is based on industrial spacecraft data from the prior missions. JPL also maintains a separate data base of current spacecraft costs to augment the historical date to reflect the change in process. Industrial partners are encouraged to participate with their latest prices. An 'out of house' process includes matching 25 characteristics required of the mission with the best fit from the industrial data base, and then determining the cost partials to upgrade (or renegotiate the science objectives) to meet the cost constraints. The results of this process, usually two weeks or six Team X sessions, is a consistent design to cost. Team X next generates the final report on-line.

The report becomes the basis for the proposal, and a smaller project proposal team takes the next few weeks to generate the proposal with 'grass roots' costs. These costs come from the Team X data originally, but are refined, considering the Implementation plans and the contractors real cost projections, which were only estimated during the sessions. It is during this phase that science may have to back off slightly, so it is good to have the rock bottom science objectives firmly identified.

If the proposal wins, the next phase is to form a small cadre of project people, and begin the requirements phase. These people would include key design engineers from each of the four process., the project scientist, and other key personnel. The next phase is for the project to generate the requirements in the cross cutting models and DOORS. The process though is reverse of the normal system engineering process. The subsystem people update the parameters data base, and the small cadre of project design people, with system engineering help, construct the cross cutting models. (See figure 8). The original Team X results represent the subsystem inputs to these models, but these inputs are updated by a new team of people from the design Hub, Team Y. The resultant requirements models are the dynamic or cross cutting specifications for the project. The exact mix of people may vary, but the intent is to produce this part of the virtual world in nine months.

DBAT

~oncLu-rent with this development is the important Behavior models from DBAT (Please see Figure 9). Recall these models capture the design at the subsystem level. They may be collections of other Behavior models, nested within the subsystem design. Construction of these models is the main purpose of the DBAT process during the design process. As we said, we believe a good implementation would be a Team Y to execute this phase. During this phase, the parameters data base is again updated, and becomes increasingly more complete. At the same time, these models arc sent to the testbed for design verification. Until the models are ready, the testbed (VIVO) has a generic subsystem capability to verify the design conceptually.

As indicated above the main attribute of the DBAT process is to construct models whereby hardware and software can be built using automatic tools. We have demonstrated on the

Cassini project an FPGA design was done just in that fashion. So we know this is possible when building electronics. What about mechanical devices?

A significant investment has also been made in a mechanical process called 'art to part' Art-to-part can automatically produce hardware from our main CAD/CAM tool Pro-E. Parts can be roughed out even while the design is still under going change, saving at lest half the cycle time.

Also, future designs call for more highly integrated designs, Micro spacecraft designs use multi functional structure. New five axis milling machines driven directly by PRO-E produce highly evolved designs, which were not possible with yesterdays approaches. Prototypes in plastic can be machined for form, fit, and function. Advanced model prototypes allow for in-line inspection by qualifying the process, which further decreases cycle time.

VIVO

The continuous verification phase is represented in Figure 10. Here we show the delivery of the subsystem designs to VIVO for testing in the Tested facilities. Eventually, flight hardware is sent in replacement of the models. It is very important for this testing to collect vital data on power, data rates, and timing to compare with the cross cutting requirements models. These results could alter the costs and schedule, so PPIC is also involved.

Figure 11 represents the final processes combined in a single diagram. This is the new third generation approach being put in place at JPL. It is expected that a basic form will be in place by March 1998. The main efforts are centered around the design of a virtual model world. Figure 12 (Reference 9) shows each of these model types in communication with the oracle data base. All of these models rests on JPL's Information System that allows execution for any of these models from anywhere at JPL, so a subsystem engineer can 'check' the specification remotely from his office.

Conclusions

The new processes describe above have been used to estimate the potential savings if wc had been ready today for the third generation evolution. Pathfinder, and Cassini were the current projects. Table 1 shows the estimated results. The projected savings is about 1 13 million, or just about the value projected from the earlier' business case. Out of a 450 million project mix, that's about twenty five percent. Now, its useful now to a step back and scc what's really going on.

From another perspective, compare the timeline of yesterdays process to the new third generation process described here. Figure 13 shows the old requirements process on the top. The new process shows a combined phase A & B shortened to nine months instead of the 18 months for Pathfinder. The new phase B contributes heavily to the up coming development phase, since we have all the subsystem behavior models in place to rapidly build hardware and software. Also, wc have already verified the design with our cross cutting models, and arc confident of the upcoming phase. In the Development phase, phases C/D there are six incremental deliveries, beginning with the intended ground system first. The Behavior models arc next followed by the on-board flight system, etc. The next to last delivery is the flight H/W, followed by a software update.

This February, 1997 represents the second delivery of the third generation system. By March of 1998, the final version will be delivered. in the meantime, pieces have already been deployed on SIRTF, Champolion, 1X3-1, and DS-3. The first of these missions, Space Infrared Telescope Facility (SIRTF), has embraced the mission verification concepts of VIVO. Champolion, a small lander is using all the concepts. DS- 1, and DS-2 arc two missions under the New Millennium program.

Acknowledgements: Original JPL DNP Team: Norm Haynes, Mike Sander, Mike Ebersole, Steve Wall, Eric Suggs, and Phil Garrison.

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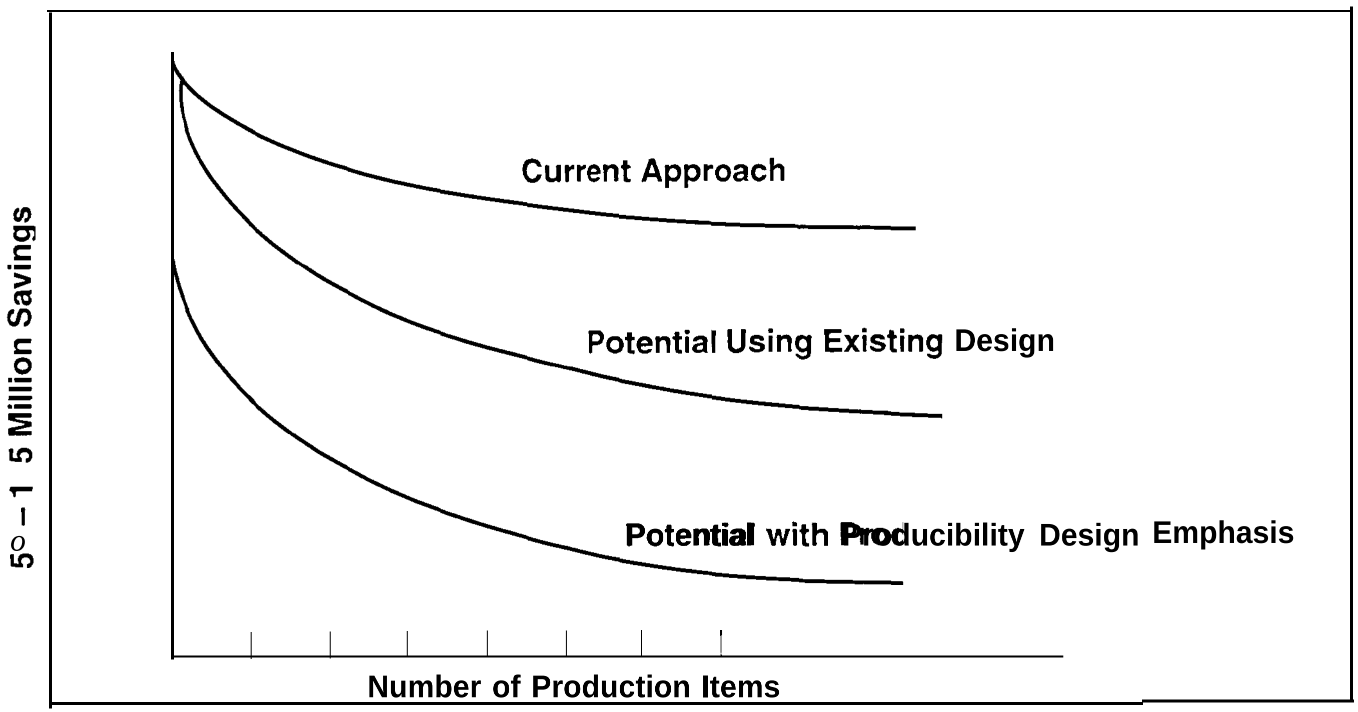
PROCESS CHANGE	ANNUAL PROJECTED SAVINGS	BASIS FOR ESTIMATE
New Team X/PDC Proposal Process	$8.25M	· 50 proposal/year • $165K average savings per proposal (ESSP) experience)
Phase B Executable Specifications/Foresight Simulations	$13.8M	• 2 major Phase B's/year: 2 AO Phase B's/year • Major Phase B average length reduced to 9 months from 18 months; AO Phase B's reduced 3 months • Major Phase B cost = $677K/month • AO Phase B cost = $300 K/month
Product Data Management for Phases B/C/D/E	$4.78M	· SHERPA/Div.35 white paper estimate
Integrated Design Architecture (all phases)	$30.0M	· 10% reduction in in-house direct (except test) due to reduced data search and re-entry • In-house direct = $450M x 2/3 = $300M (non-test related)
Integrated Mission Testbed	$30M	· 207. Phase C/D savings due to early problem identification and resolution • S 150 in house annual Phase C/D test costs • 6 deliveries/two months apart – reduced testing time 18 to 20 months
Strategic Stockpile	$15M	• 5% reduction in phase C/D length/costs due to reduced procurement lead-time
Art-to-Part (Mechanical	$6.7M	· 2/3 reduction in fabrication time/cost of mechanical components · $10M/year total in-house fabrication expenditures
Art-to-Part (Electrical)	$2M	· 20% reduction in fabrication costs of electrical components from behavioral modeling • $10M/year total electrical component fabrication costs
Reengineered Project Planning/Management Process	$3M	· 107c annual savings in project planning/management in Phase C/D • $30M/year total Phase C/D planning/management costs
Total Annual Savings	!3113.53M	

Table 1.



Ref: The Joint Strike Fighter Program - July 1996

Figure 1. Learning Curve Improvement Potential

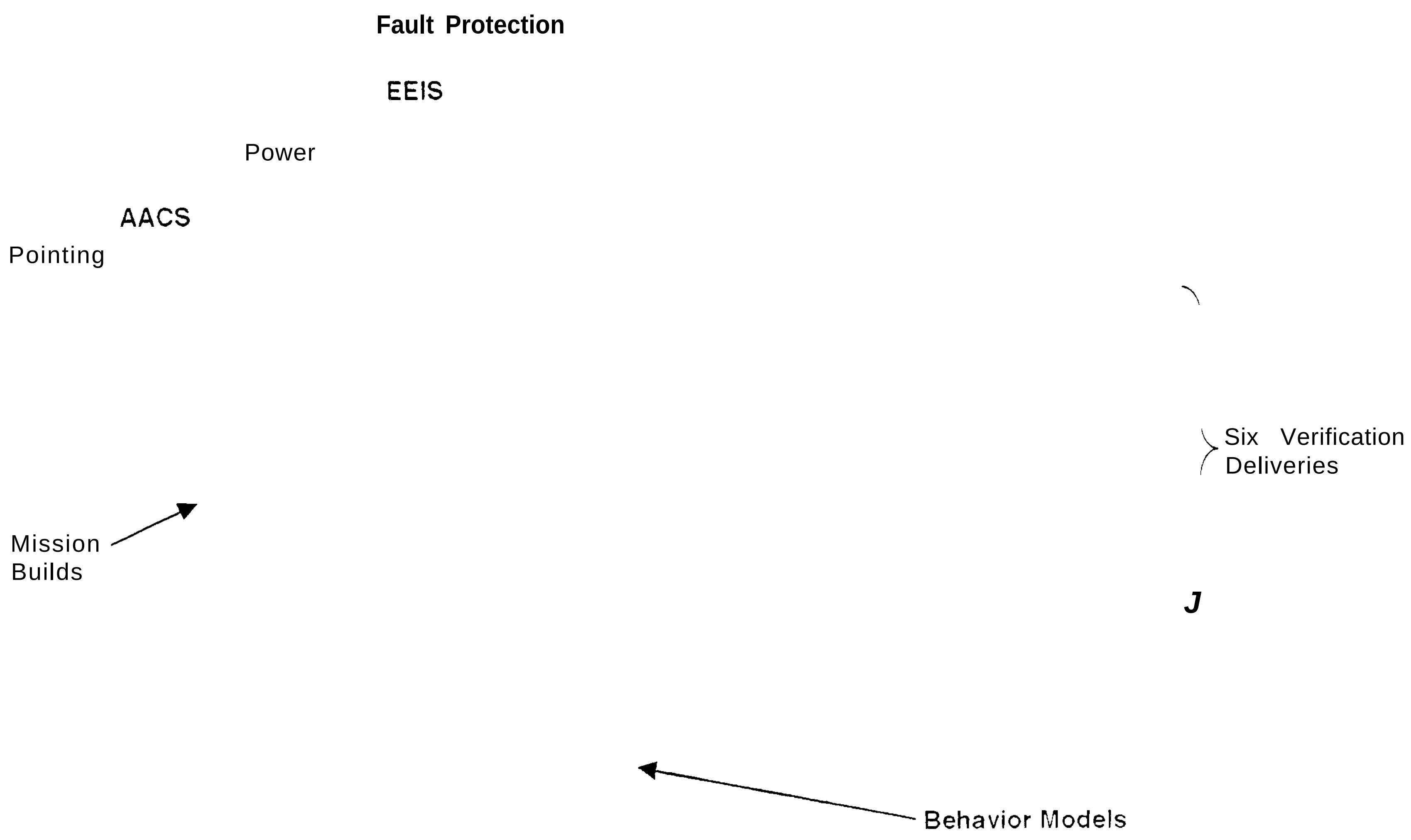


Figure 2. Model Interaction

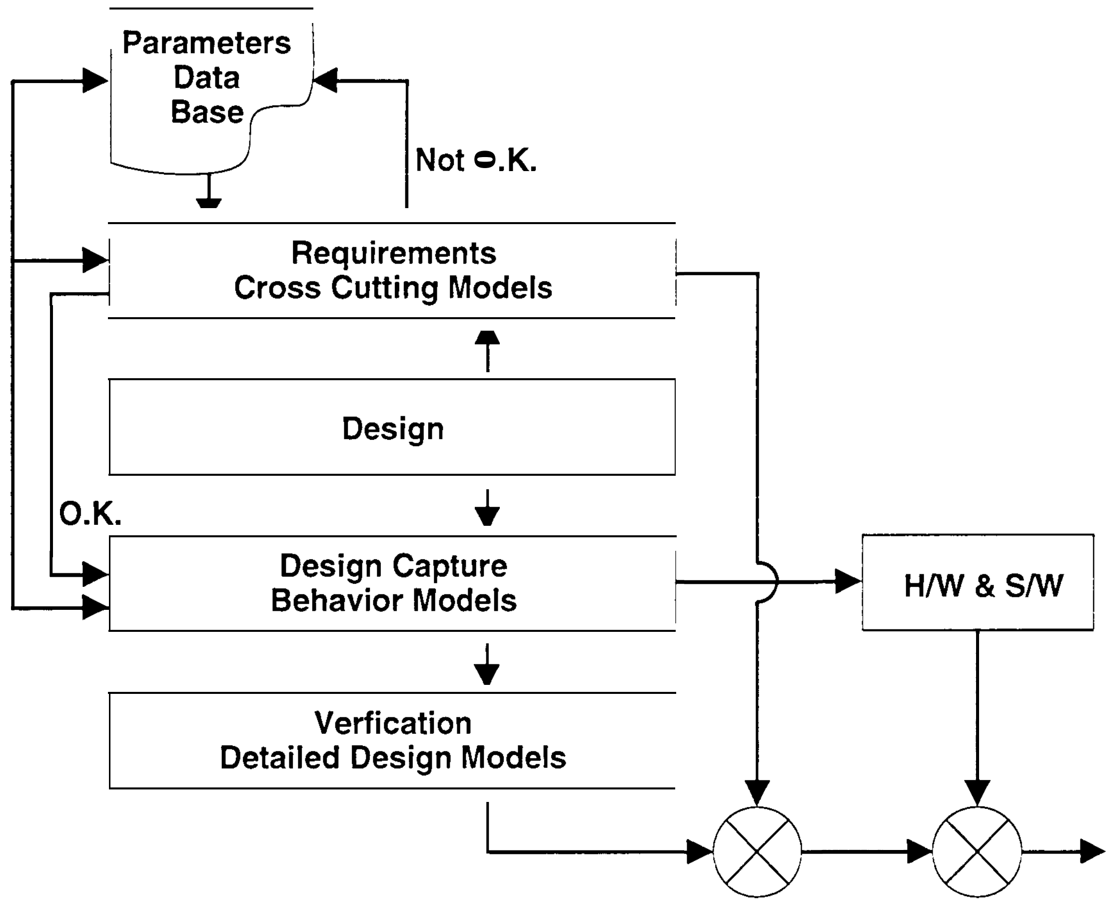


Figure 3. Model Types

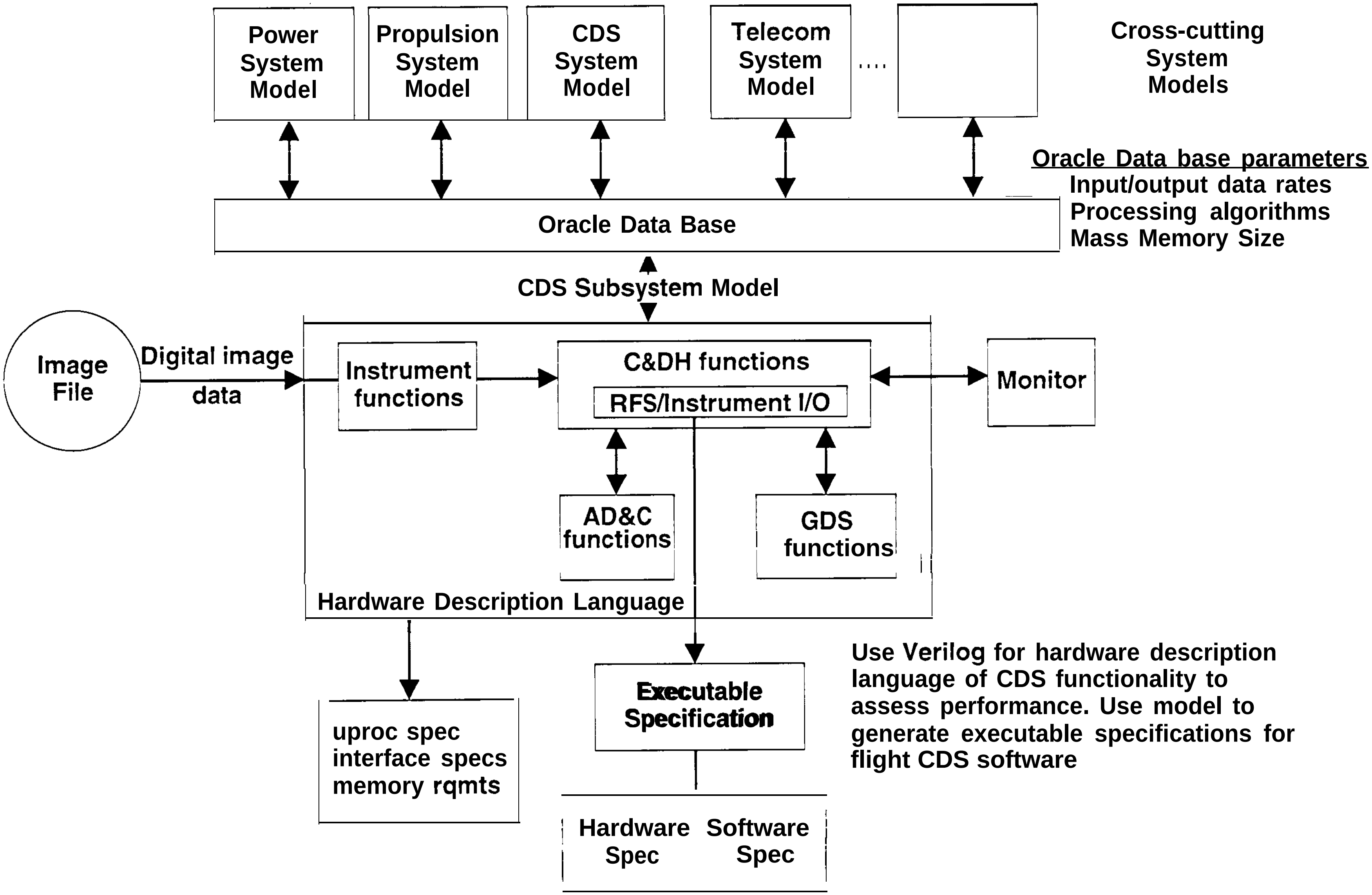


Figure 4. DNP DBAT CDS Model Block Diagram

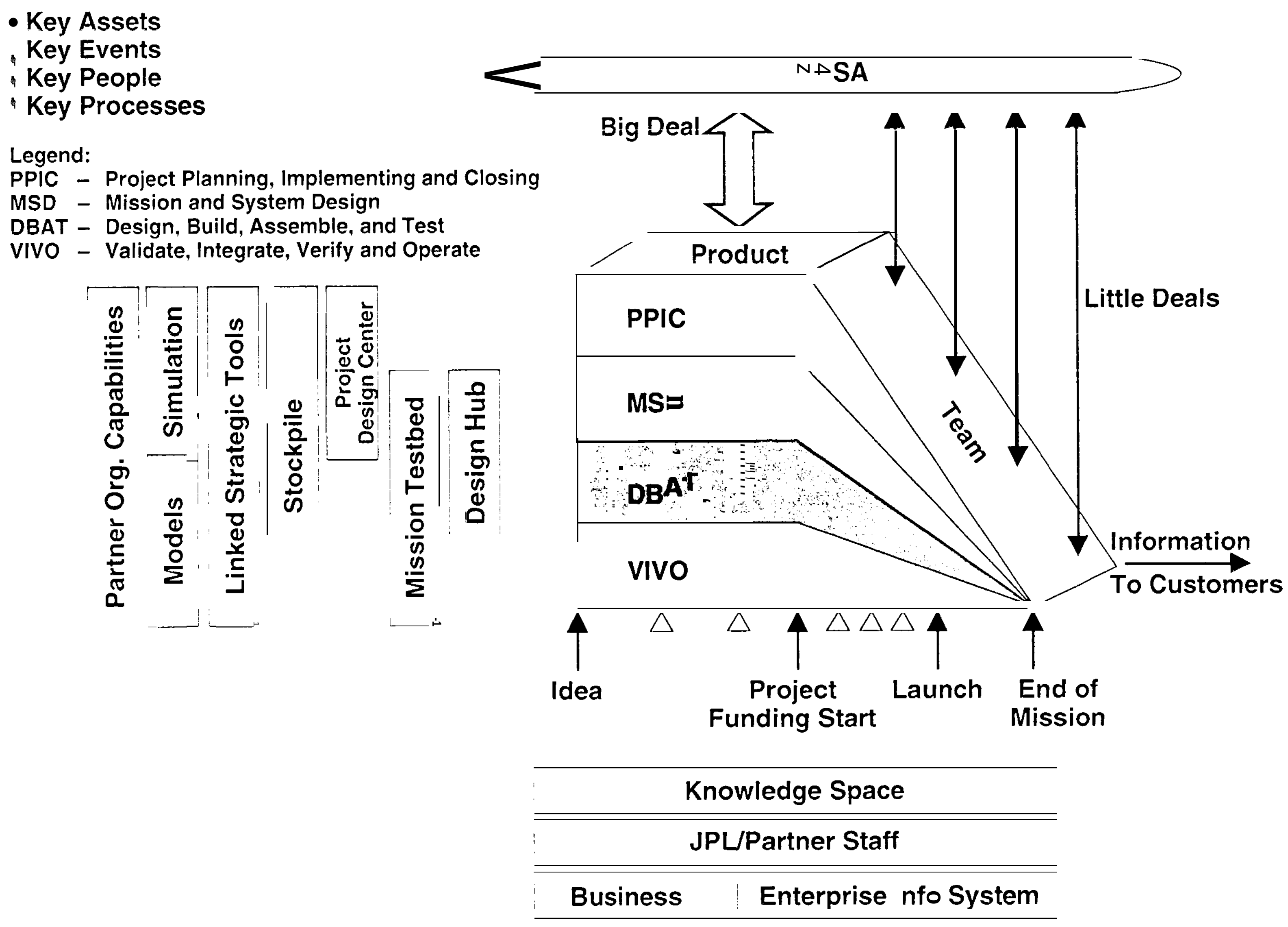


Figure 5. JPL Develop New Products Process Model

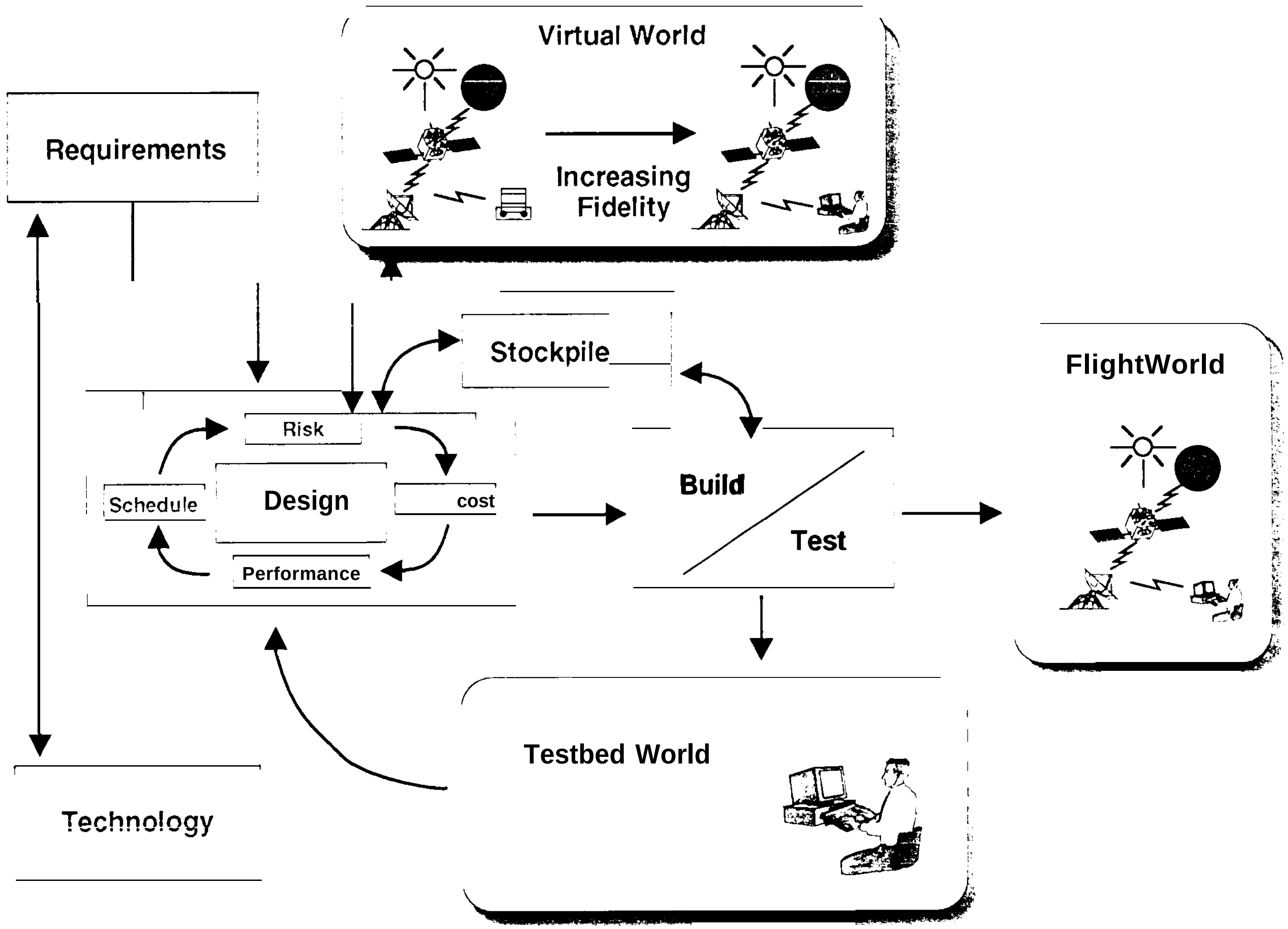


Figure 6. "Three World" Development Process

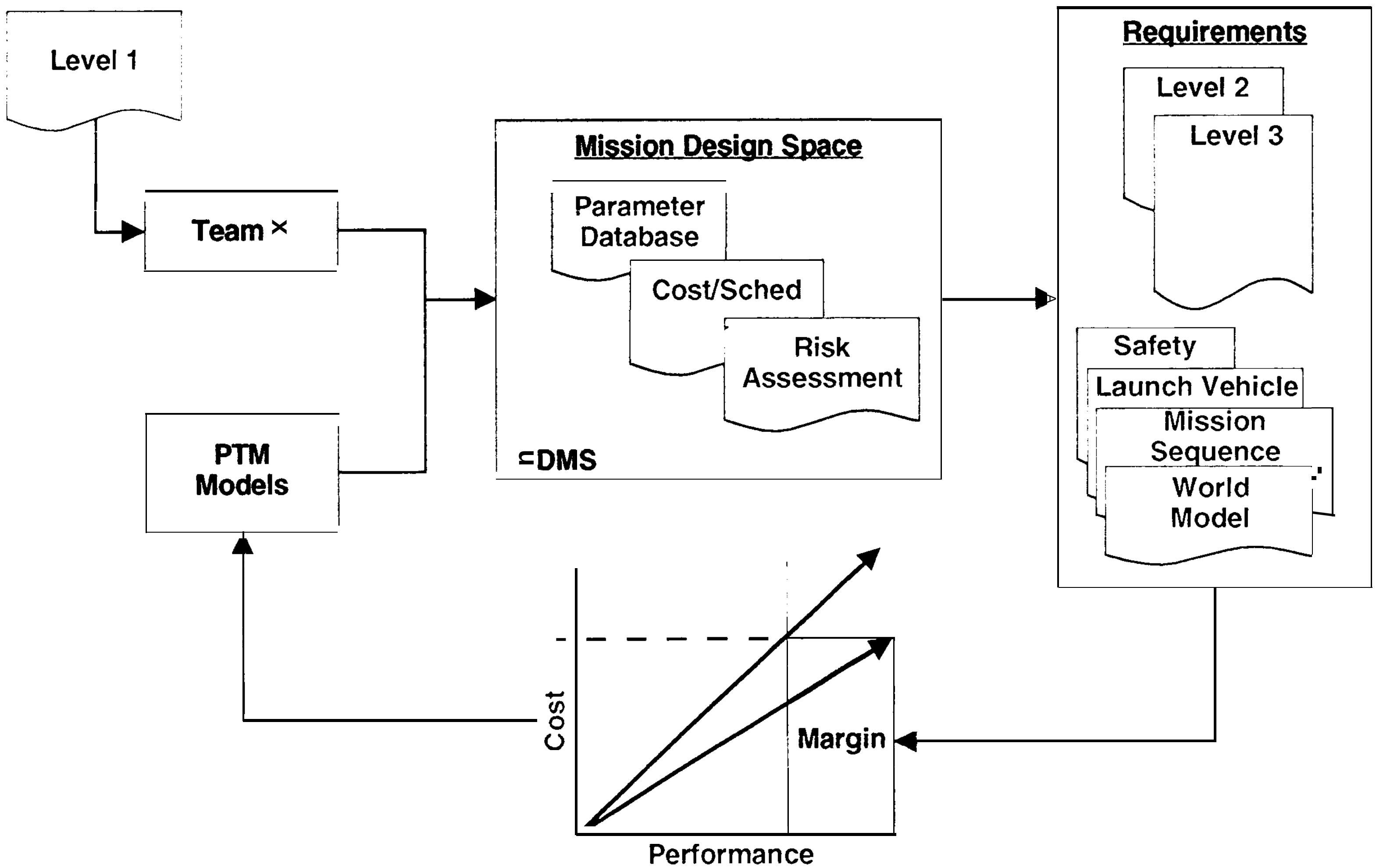


Figure 7. Pre-Project Design to Cost

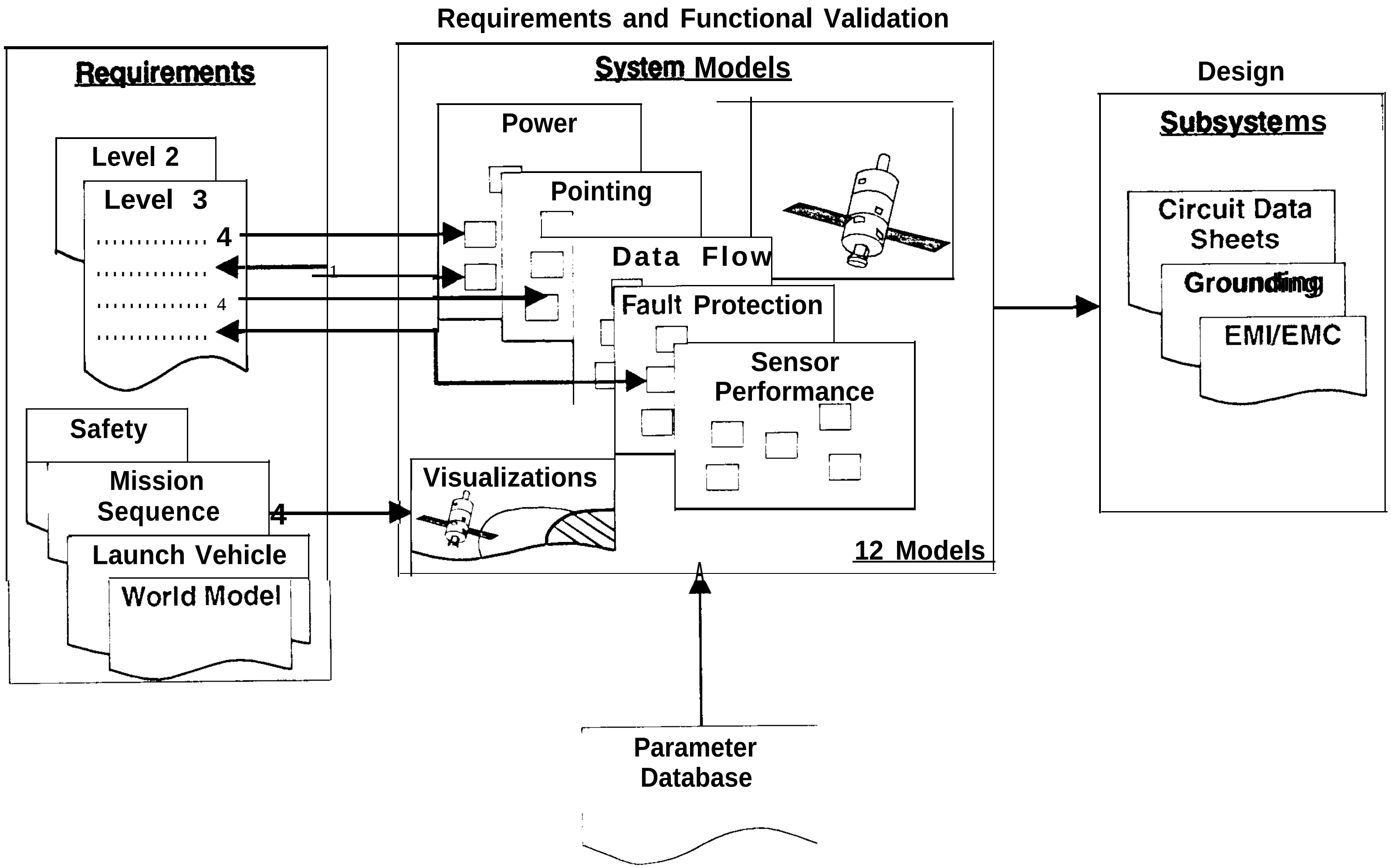


Figure 8. Project Design

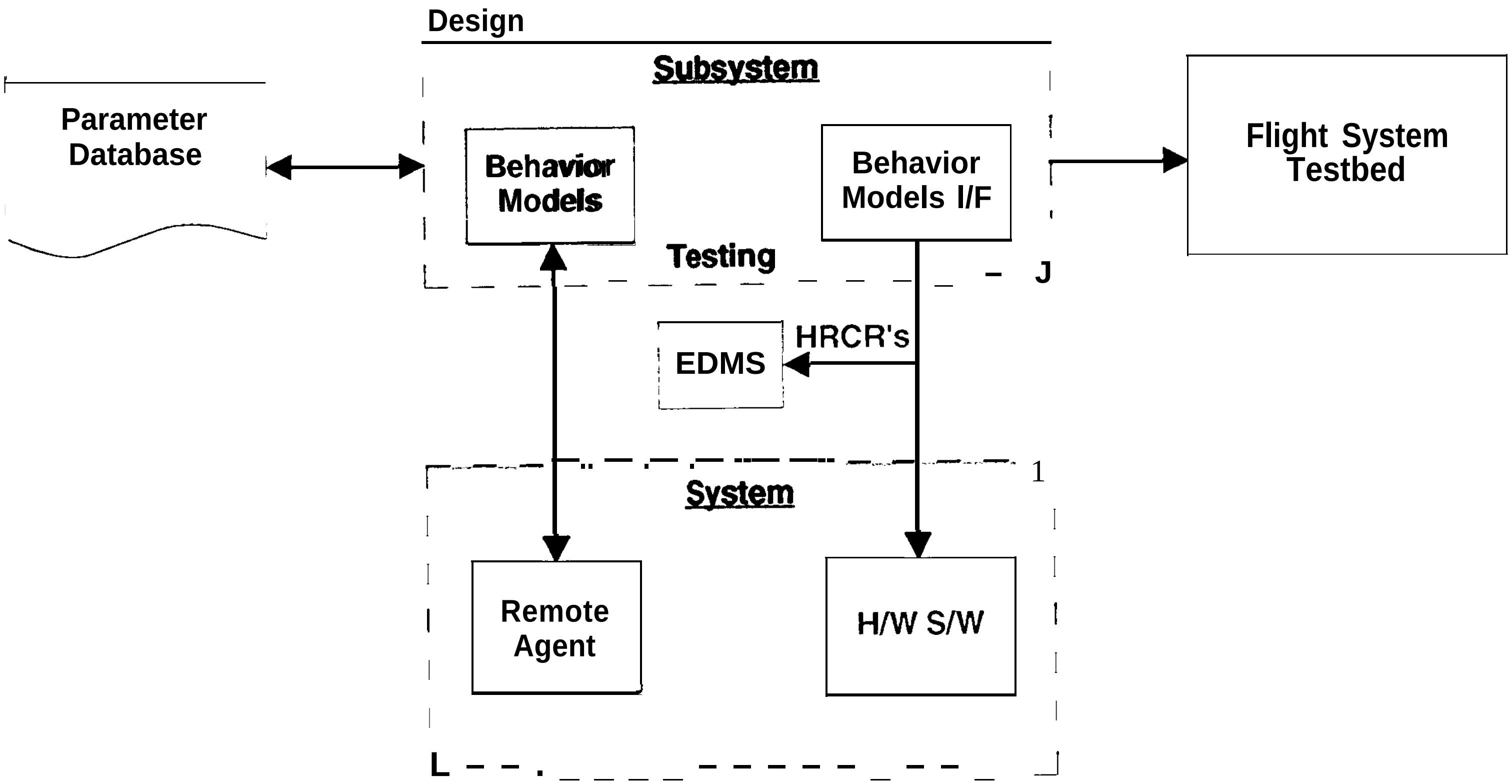


Figure 9. Project Design

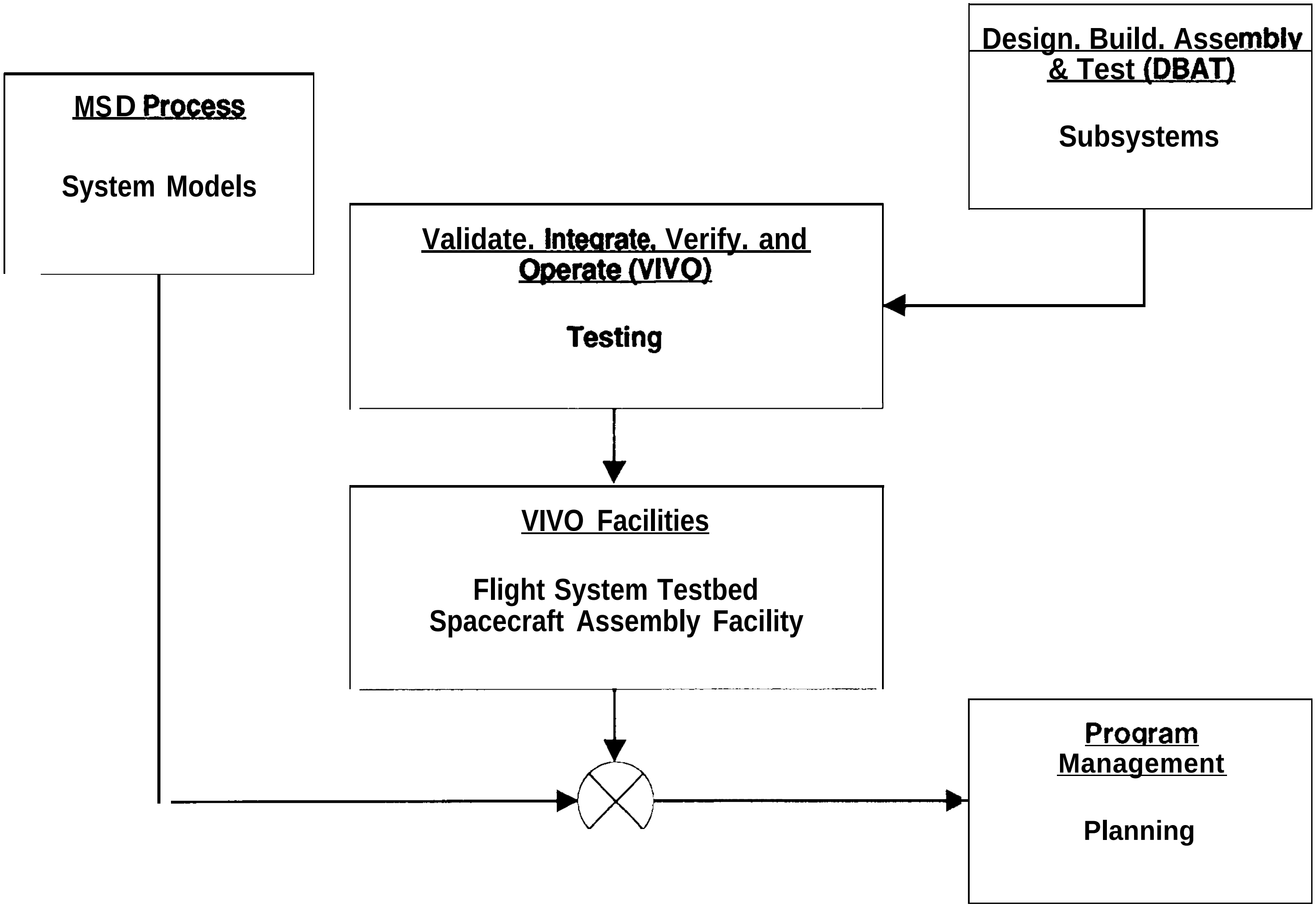


Figure (). DNP System Engineering Process Build and Test

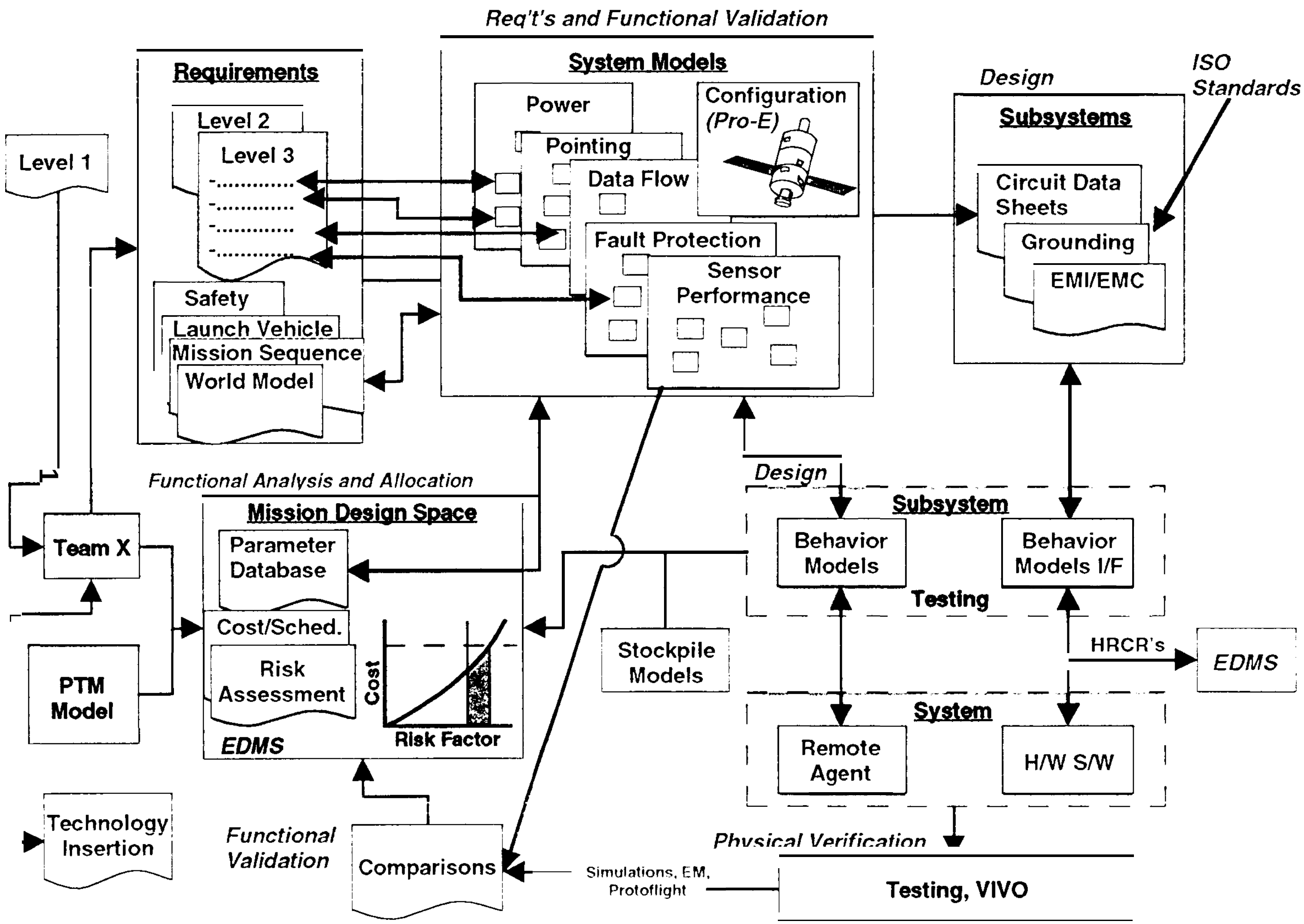


Figure 1 DNP System Engineering Process

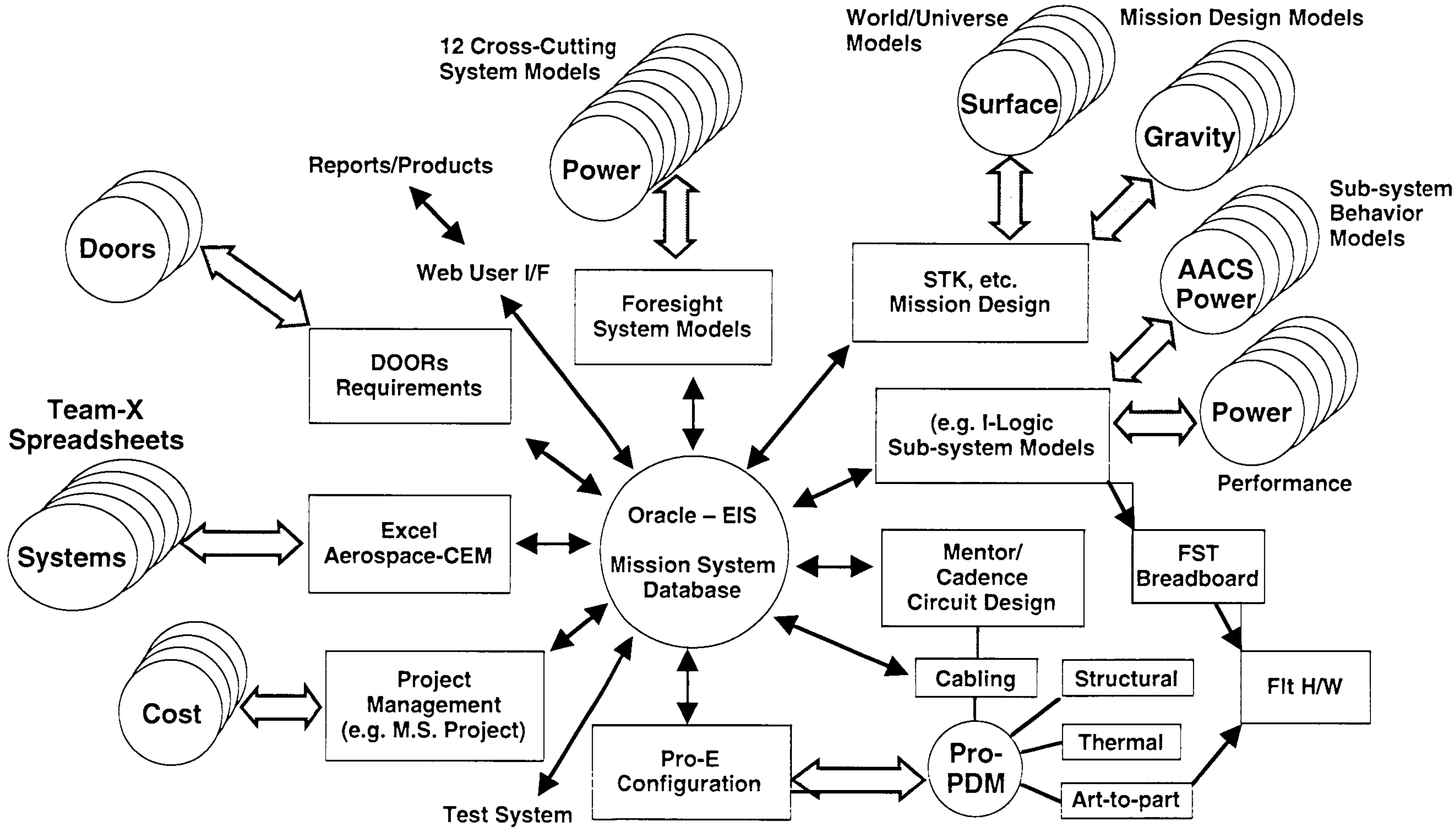


Figure 12. Information System Architecture

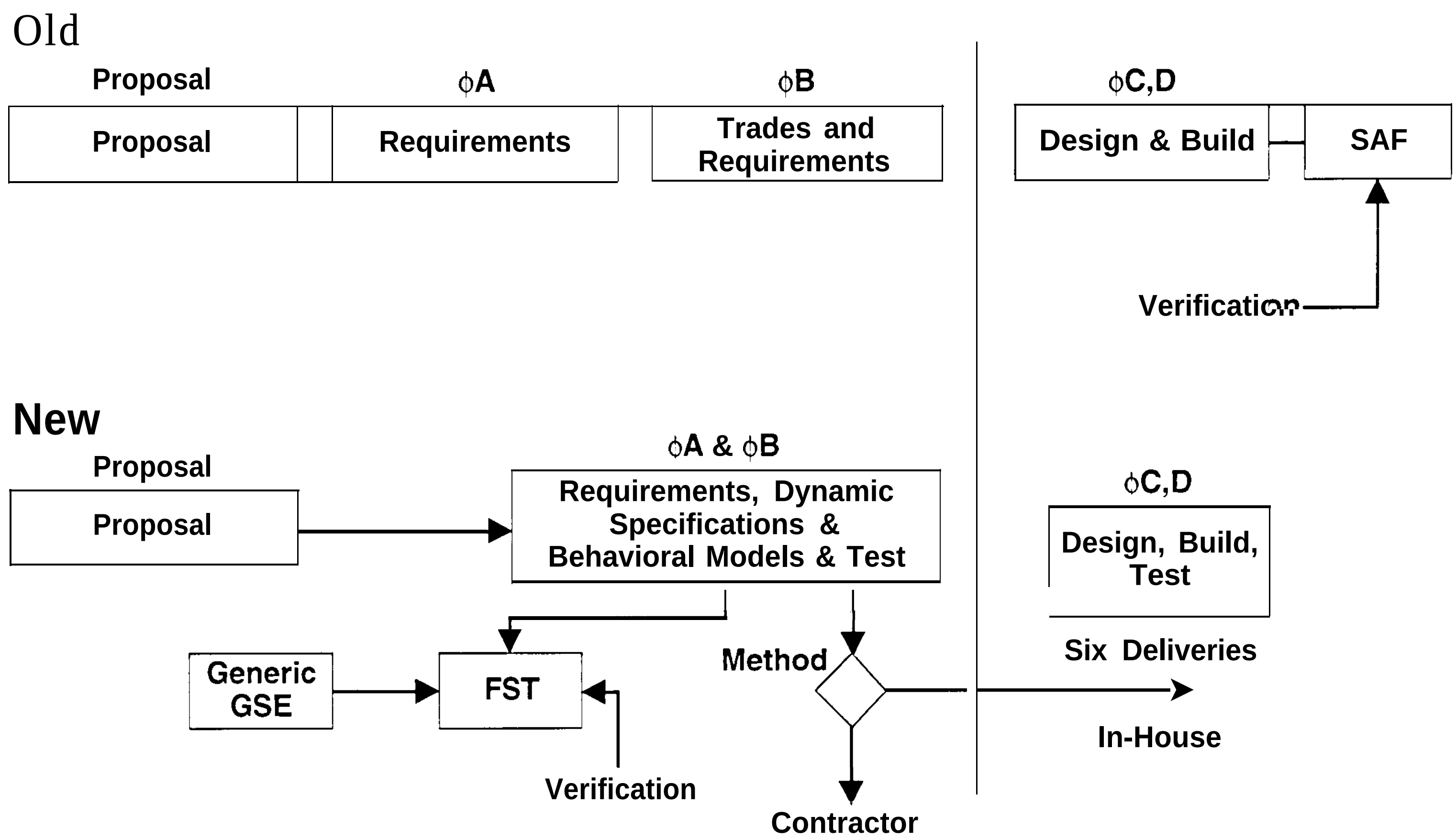


Figure 13. DNP Process Comparison