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PROPOSAL OF A TRADE OFF DECISION SUPPORT SYSTEM THROUGH INTEGRATIVE PARAMETERS FOR SATELLITE DESIGN PROCESS

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Abstract. *In the product development early phases, the management of changes deserves special attention. One the most difficult aspects of the product development process is to recognize, understand and manage the trade-offs in a way that maximizes the success of the product. This is particularly important for space projects. Integrative parameters can be identified to support trade off decision made through the study of system engineering process and the techniques used in product development processes. The proposal presented in this paper provides a means for innovating the spacecraft design process by interconnecting user needs, critical parameters and critical characteristics with the integrative parameters in order to integrate the trade off process with the product development. The reasons for turning the process integrated in the trade off decision support system are: attempt to the user's needs (QFD to connect user's needs with critical requirements and critical parameters); use of critical requirements to perform functional analysis; use of critical requirements as goals/objectives and constrains in the trade off process; use of critical characteristics to identify trade off areas; use of integrative parameters as measures to support evaluation; use of integrative parameters to define the selection rules (efficient solutions based on integrative parameters). Therefore, the use of QFD and integrative parameters implements the concept exploration flow and the trade off integration.*

Key words*: satellite; trade-off; integrative parameters; design process.*

2. Introduction

Systems engineering is performed concurrently with system management. A major part of the system engineer's role is to provide information that the system manager can use to make the right decisions. This includes identification of alternative design concepts and characterization of those concepts. This work is to help the system managers first discover their preferences, and then be able to apply them astutely. An important aspect of this role is the creation of system models that facilitate alternatives assessment in various performance dimensions such as power, mass, size, and on orbit lifetime.

An effective system must provide a particular kind of balance among critical parameters. An ideal solution should meet high performance requirements in all technological areas. This is a very difficult goal to reach because the successful in one area could represent failure in other. Figure 1 shows a radar graph with performance possibilities of a particular design. Points outside of the radar graph cannot be achieved with currently available technology, that is, they do not represent feasible designs. Some of those points may be feasible in the future, when further technological advances have been made. Points inside the envelope are feasible, but are dominated by designs that combine best parameters in the radar graph.

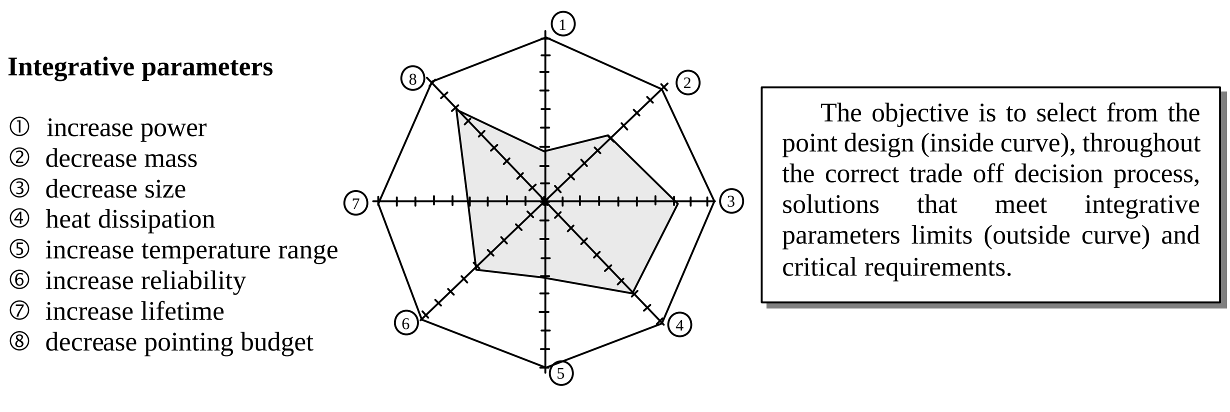

Figure 1. Radar graph with design solution possibilities.

Design trade off studies, an important part of the systems engineering process, often attempt to find designs that provide a better combination of the various performance dimensions or effectiveness. When the starting point (solution) for a design trade off study is inside the radar, there are alternatives that increase some aspect of effectiveness without decrease other aspect.

In space projects, such as satellite design process, one of the system engineering purposes is the integration and control of the various technical areas and participants throughout all the project phases. It provides corresponding inputs to project management in order to optimize the total definition and execution of the product. The process is generally exercised primarily at top level during the early project phases and addresses lower levels as the project progress. In the early phases, the management of changes deserves special attention. One the most difficult aspects of the product development process is to recognize, understand and manage the trade-offs in a way that maximizes the success of the product. This is particularly important for space projects. Integrative parameters can be identified to support trade off decision made through the study of system engineering process and the techniques used in product developments. The overall goal of this work is to find out and understand the relationship among the integrative parameters and trade-offs carried-out during space projects to implement the integrated product development in a space project environment. A real space project has been chosen as the platform, which provides the information for this study in order to implement posterior methodology.

3. Satellite development process and the “Vee” chart

The project planning is usually structured into sequential phases. The start up of a new phase depends generally from a milestone to be met. Although each phase is a part of a sequential logic, the start of the next phase can be decided before all tasks of the current phase are fully completed. In this case, induced risks have to be clearly identified. The overlapping of the activities of different phases does not prevent responsibility for the phases from being assigned to different lead actors. Usually a project is broken down into seven – NASA approach – or six - ESA approach - major phases as shown in Fig. 2.

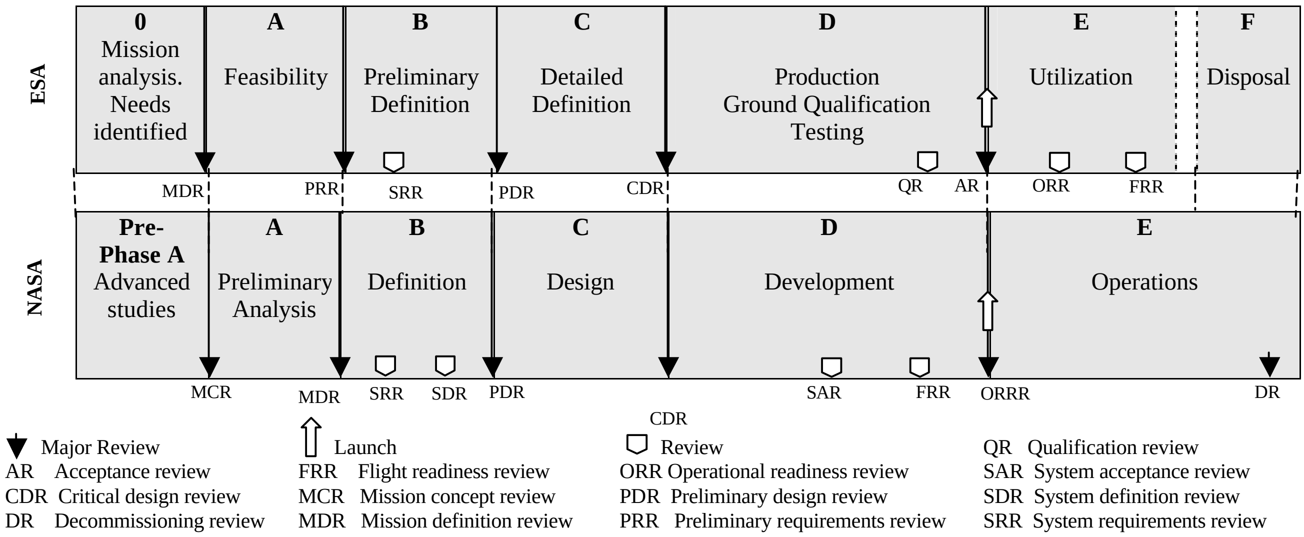

Figure 2. Satellite development phases (Larson, and Wertz, eds. 2003).

The sequence of activities on a system or a product, and their links, form a typical life cycle. The sequence of reviews starts at the highest level for requirements and definition (MDR, PRR, SRR, PDR) and at the lowest levels for justification and verification (CDR, QR, AR).

Forsberg and Mooz (1991) describe what they call "the technical aspect of the project cycle" by a Vee-shaped chart, starting with user needs on the upper left and ending with a user-validated system on the upper right. Figure 3 provides a summary level overview of those activities. On the left side of the “Vee”, decomposition and definition activities resolve the system architecture, creating the details of the design. Integration and verification flow up and to the right as successively higher levels of subsystems are verified, culminating at the system level.

At each level of the “Vee”, systems engineering activities include off-core processes: identify and quantify goals, create concepts, do trade off studies and select design. These activities are performed at each level and may be repeated many times within a phase. While many kinds of studies and decisions are associated with the off-core activities, only decisions at the core level are put under configuration management at the various control gates. Off-core activities, analyses, and models are used to substantiate the core decisions and to ensure that the risks have been mitigated or determined to be acceptable. The off-core work is not formally controlled, but the analyses, data and results should be archived to facilitate replication at the appropriate times and levels of detail to support introduction into the baseline.

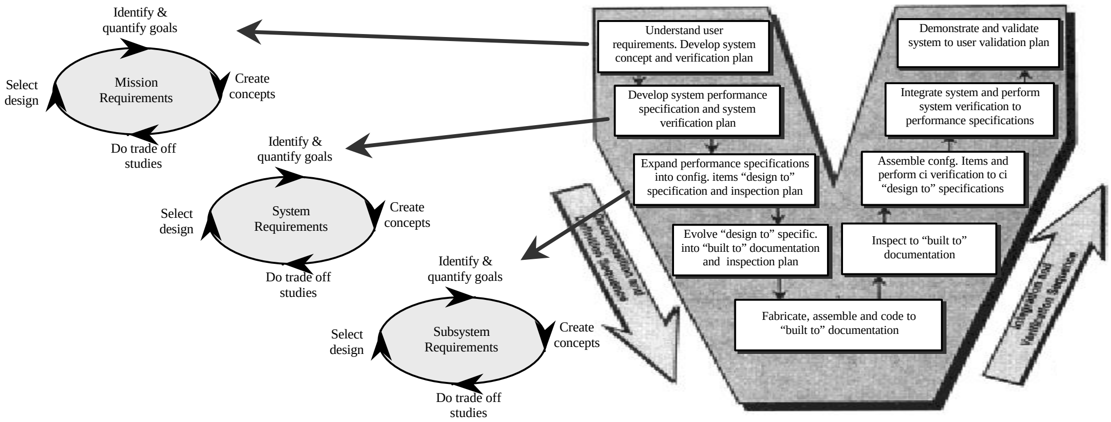

Figure 3. Successive refinement in the "Vee" chart.

As the product development progresses, a series of baselines is progressively established, each of which is put under formal configuration management, at the time, it is approved. Among the fundamental purposes of configuration management is to prevent requirements from "creeping".

The left side of the core of the "Vee" is similar to the so-called "waterfall" or "requirements-driven design" model of the product development process. The control gates define significant decision points in the process. Work should not progress beyond a decision point until the project manager is ready to publish and control the documents containing the decisions that have been agreed upon at that point.

However, there is no prohibition against doing detailed work early in the process. In fact, detailed hardware and/or software models may be required at the very earliest stages to clarify user needs or to establish credibility for the claim of feasibility. Early application of involved technical and support discipline is an essential part of this process; this is in fact implementation of concurrent engineering (Shinko, 1995).

4. The concept flow and trade off process

The realization of a system over its life cycle results from a succession of decisions among alternative courses of action. If the alternatives are precisely enough defined and thoroughly enough understood to be well differentiated in the effectiveness space, then the system manager can make choices among them with confidence.

The systems engineering process can be thought of as the pursuit of definition and understanding of design alternatives to support those decisions, coupled with the overseeing of their implementation.

Most of the major system decisions (requirements, architecture, acceptable life-cycle cost, etc.) are made during the early phases of the project, so the process presented in Fig. 4 turns spiral (with successive refinements) and do not correspond precisely to the phases of the system life cycle. Much of the system architecture can be "seen" even at the outset, so the turns of the spiral do not correspond exactly to development of the architectural hierarchy, either. Rather, they correspond to the successively greater resolution by which the system is defined.

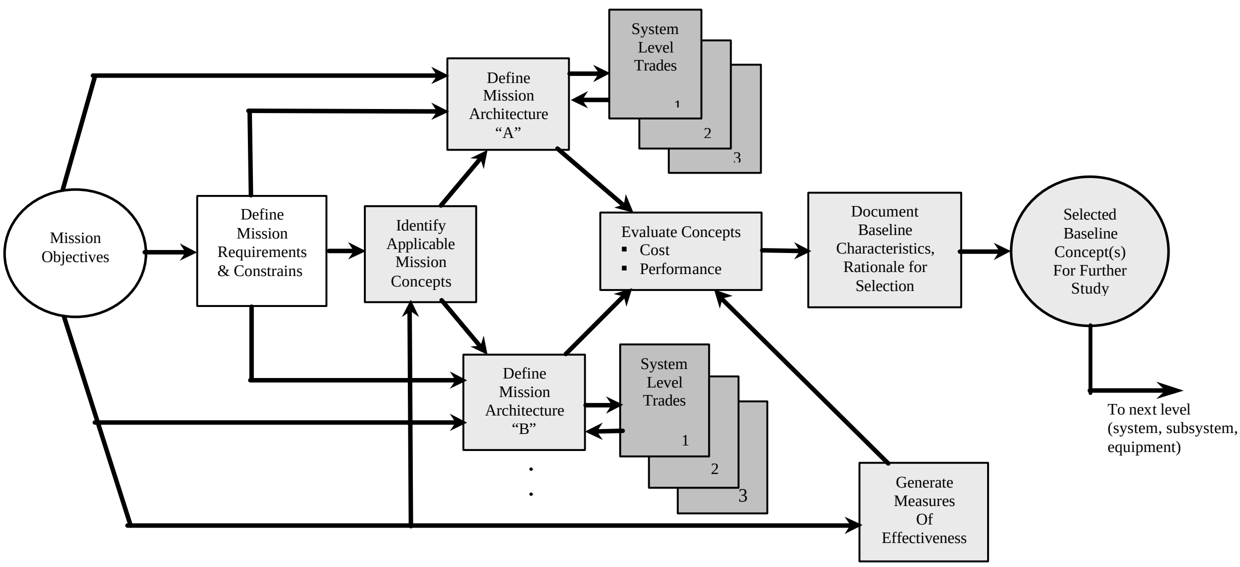

Figure 4. Concept exploration flow (Larson, and Wertz, eds. 2003).

The trade off process is a critical part of the systems engineering spiral described. Figure 5 shows the trade off process in simplest terms.

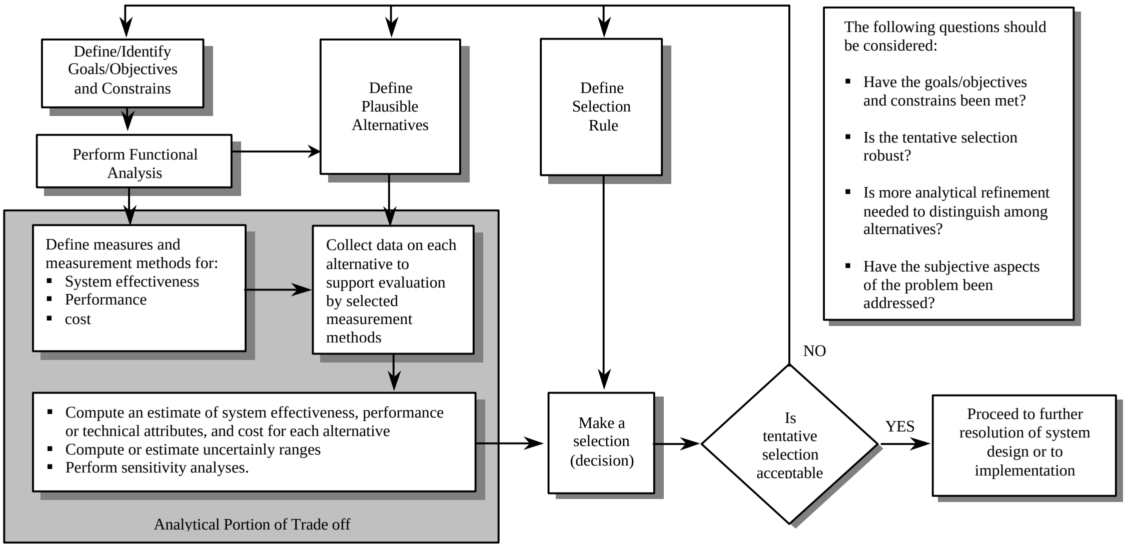

Figure 5. Trade off process (Shinko, 1995).

The purpose of the trade off process is to ensure that they move the design toward an optimal stage throughout successive refinements of system architecture and design decisions. The basic steps of this process are:

- Understand what the system's goals, objectives, and constraints are, and what the system must do to meet them—that is, understand the functional requirements in the operating environment.
- Devise some alternative means to meet the functional requirements. In the early phases of the project life cycle, this means focusing on system architectures; in later phases, emphasis is given to system designs.
- Evaluate these alternatives in terms of the outcome variables (system effectiveness, its underlying performance or technical attributes, and system cost). Mathematical models are useful in this step not only for forcing recognition of the relationships among the outcome variables, but also for helping to determine what the performance requirements must be quantitatively.
- Rank the alternatives according to an appropriate selection rule.
- Drop less-promising alternatives and proceed to next level of resolution, if needed.

This process cannot be done as an isolated activity. To make it work effectively, individuals with different skills—system engineers, design engineers, specialty engineers, program analysts, decision scientists, and project managers—must cooperate. The right quantitative methods and selection rule must be used. Trade study assumptions, models, and results must be documented as part of the project archives.

5. Trade off support system (TOSS)

Although essentially all missions go through mission evaluation and analysis stages many times, there are relatively few discussions in the literature of the general process for doing this (Larson and Wertz, eds. 2003). Fortescue and Stark (1995) discuss the process for generic missions; Przemieniecki (1993, 1994) does so for defense missions. Kay (1995) discusses the difficulty of doing this within the framework of a political democracy and Wertz and Larson (1996) provide specific techniques applicable to reducing mission cost.

The main objective of the trade off support system is to integrate the concept exploration flow and the traditional trade off process. This is carried out using QFD tool and integrative parameters. In this way, the trade offs are carried out throughout characteristics (critical characteristics) that most affect the critical requirements, having as function objective the integrative parameters optimization and the critical requirements accomplished. The integrative parameters are those that influence in global way the product performance.

The steps of the trade off support system are:

Step 1.To perform QFD – Quality Function Deployment to obtain critical requirements:

Quality Function Deployment involves a series of matrices organized to define system characteristics and attributes and can be applicable over multiple areas.

The first matrix, connecting customer’s needs or user’s needs to mission requirements, is often called “House of Quality”. The output of this process is the election of “critical requirements”.

Critical requirements are those that dominate the space mission’s overall design and, therefore, most strongly affect performance and cost. The critical requirements are used as goals/objectives and constrains.

Step 2.To perform function analysis:

Functional analysis is the systematic process of identifying, describing, and relating the functions that a system must perform in order to fulfil1 its goals and objectives or its critical requirements.

Step 3.To perform QFD – Quality Function Deployment to obtain critical characteristics:

The second QFD matrix connects critical requirements defined by the first “House” to technical characteristics. After that, the most important technical characteristics are called “critical characteristics”.

Critical characteristics are those that are most affected by critical requirements. They are used to define plausible alternatives that most are affected by critical requirements.

Table 1 lists the most common critical requirements and the areas they typically affect.

Table 1. Common critical requirements.

Critical requirement (trade parameter)	**What it affect (characteristics or trade off areas)**
Camera resolution	Instrument size, altitude
Camera sensitivity	Payload size, thermal control
Transmit power	Payload size and power, altitude
On orbit lifetime	Redundancy, weight, power and propulsion budgets

Thus the QFD is a structured means for a design team to address customer needs and to develop the consequent design characteristics to satisfy them. It also serves to sustain the trail of requirements derivation and provides a means for analyzing the impact of changes to requirements at any level.

Step 4. To define plausible alternatives:

Defining plausible alternatives is the step of creating some alternatives that can potentially achieve the critical requirements of the system. This step depends on understanding (to an appropriately detailed level) the system's functional requirements and operational concept. Creating alternatives through functional analysis and critical characteristics helps the designer to define concepts that are dominated by critical requirements. Defining plausible alternatives also requires an understanding of the technologies available, or potentially available, at the time the system is needed.

Step 5. To define integrative parameters:

Integrative parameters are the principal system drivers or characteristics which influence performance, cost, risk or schedule and which the user or designer can control. For (Larson and Wertz, eds. 2003), correctly identifying the key system drivers is a critical step in mission analysis and design. Misidentifying integrative parameters is one of the most common causes of mission analysis error.

Table 2 lists the most common integrative parameters and the limits associated with them.

Table 2. Common integrative parameters.

Integrative parameters	**What limits integrative parameter**	**What integrative parameter limits**
Size	Bay size, available weight, aerodynamic drag	Payload size (antenna diameter)
On orbit weight	Altitude, inclination, launch vehicle	Survivability
Power	Size, weight,	Payload and bus design, on orbit life
Pointing	Cost, weight	Resolution, accuracy

The integrative parameters are used as measures for system effectiveness and performance in the trade off support system (TOSS).

Step 6. To collect data on each alternative to support evaluation:

The next step is to collect data on each alternative to support the evaluation of the integrative parameters by the selected measurement methods. If models are to be used to calculate some of these integrative parameters, then obtaining the model inputs provides some impetus and direction to the data collection activity. By providing data, engineers in such disciplines as reliability, maintainability, productibility, integrated logistics, software, testing, operations, and costing have an important supporting role in trade off studies. The system engineer, however, should orchestrate the data collection activity. The results of this step should be a quantitative description of each alternative in terms of integrative parameters to accompany the qualitative.

Step 7. To perform the analytical portion of the trade off system:

The next step in the trade off process is to quantify the outcome variables by computing estimates of system effectiveness, its underlying integrative parameters. If the needed data have been collected, and the measurement methods (for example, models) are in place, then this step is, in theory, mechanical. In practice, considerable skill is often needed to get meaningful results.

In an ideal world, all input values would be precisely known, and models would perfectly predict outcome variables. This not being the case, the system engineer should supplement point estimates of the outcome variables for each alternative with computed or estimated uncertainty ranges. For each uncertain key input, a range of values should be estimated. Using this range of input values, the sensitivity of the outcome variables can be gauged, and their uncertainty ranges calculated. The system engineer may be able to obtain meaningful probability distributions for the outcome variables, but when this is not feasible, the system engineer must be content with only ranges and sensitivities.

Step 8. To define selection rule:

Many different selection rules are possible. The selection rule in a particular trade off may depend on the context in which the trade off is being conducted—in particular, what level of system design resolution is being addressed. At each level of the system design, the selection rule generally should be chosen only after some guidance from the next higher level. The selection rule for trade offs at lower levels of the system design should be in consonance with the higher level selection rule.

The selection rule is the step of explicitly determining how the integrative parameters will be used to make a (tentative) selection of the preferred alternative. The objective can be to select the concept that meets the yield curve. The possibility of this happen is increased by the implementation of the trade off support system (TOSS).

Figure 6 shows the elements of the trade off support system (TOSS).

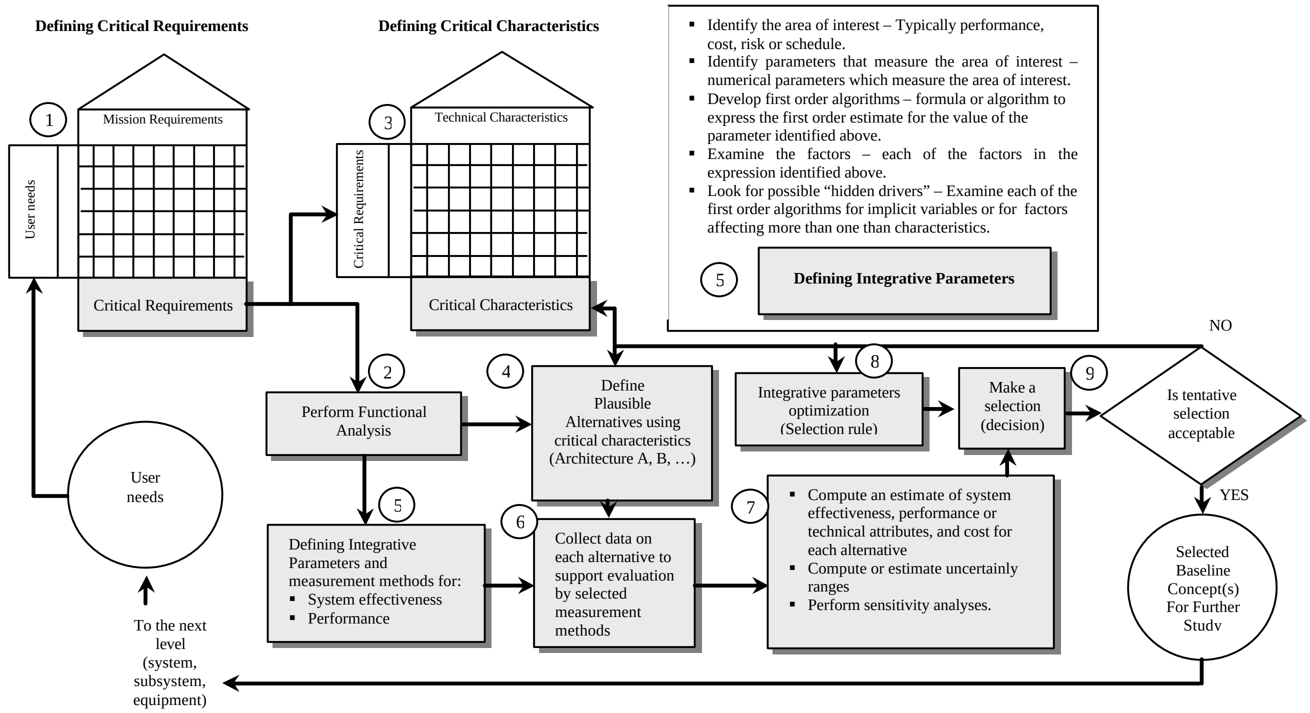

Figure 6. Trade off support system (TOSS).

Step 9. To make a selection:

This essentially completes the analytical portion of the trade off process. Combining the selection rule with the results of the analytical activity should enable the system engineer to array the alternatives from most preferred to least, in essence making a tentative selection. This tentative selection should not be accepted blindly. In most trade off studies, there is a need to subject the results to a "reality check" by considering a number of questions. Have the goals, objectives, and constraints truly been met? Is the tentative selection heavily dependent on a particular set of input values to the measurement methods, or does it hold up under a range of reasonable input values? (In the latter case, the tentative selection is said to be robust.) Are there sufficient data to back up the tentative selection? Are the measurement methods sufficiently discriminating to be sure that the tentative selection is really better than other alternatives? Have the subjective aspects of the problem been fully addressed?

If the answers support the tentative selection, then the system engineer can have greater confidence in a recommendation to proceed to a further resolution of the system design, or to the implementation of that design.

If the reality check is not met, the trade off study process returns to one or more earlier steps. This iteration may result in a change in the goals, objectives, and constraints, a new alternative, or a change in the selection rule, based on the new information generated during the trade study. The reality check may, at times, lead instead to a decision to first improve the measures and measurement methods (e.g., models) used in evaluating the alternatives, and then to repeat the analytical portion of the trade off process.

6. Conclusions

Design methodologies present product development process in a systemize and organized way, however, the same do not occur in relation with information and activities about the creation and evaluation of design alternatives. There are relatively few discussions about the trade off process in the literature.

A lot of trade off decisions are taken in the design development process, such as:

- Support decisions for new products and process developments versus non–developmental product and processes.
- Establish System and Configuration items.
- Assist in selecting system concepts, designs and solutions (including people, parts and materials availability).
- Support material selection and make–or–buy, process, estimation and location decisions.
- Analyze planning critical paths and propose alternatives.
- Examine alternative technologies to satisfy functional/design requirements including alternatives for moderate to high-risk technologies.
- Evaluate environmental and cost impacts of materials and processes.
- Evaluate alternative physical architectures to select preferred products and processes.
- Select standard components, techniques, services and facilities that reduce System life–cycle cost and meet System effectiveness requirements. Agencies and commercial data bases should be utilized to provide historical information used in evaluation decisions.
- Assess model philosophy demonstrating qualification objectives and verification goals as well as testability needs.
- Assess design capacity to evolve.

The objective of an efficient trade off is to find out, among alternatives, a design that provides a better combination of the various effectiveness dimensions. Thus, design trade offs are an important part of the systems engineering process.

The proposal presented in this paper provides a means for innovating the spacecraft design process by interconnecting user needs, critical parameters and critical characteristics with the integrative parameters in order to integrate the trade off process with the product development.

The role of integrative parameters in the trade off support system is to take the design to the efficient solution throughout integration.

The reasons for the development process turns integrated are:

- Attempt to the user's needs (QFD to connect user's needs with critical requirements and critical parameters);
- Use of critical requirements to perform functional analysis;
- Use of critical requirements as goals/objectives and constrains in the trade off process;
- Use of critical characteristics to identify trade off areas;
- Use of integrative parameters as measures to support evaluation;
- Use of integrative parameters to define the selection rules (efficient solutions based on integrative parameters);

The objective is to select from the point design (inside curve), throughout the correct trade off decision process, solutions that meet integrative parameters limits (outside curve) and critical requirements in all design levels (system, subsystem, equipment, parts and components).

Design environments, such as the trade off process, are dependant on the successful interaction of multiple teams and multiple stakeholders. Defining, capture and using integrative parameters as measures in a trade off process promote the required team integration and management decisions.

Therefore, the use of QFD and integrative parameters implements the concept exploration flow and the trade off integration.

A real space project has been chosen as the platform, which provides the information for a case study in order to implement posterior methodology. This case study is in elaboration phase.

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8. Responsibility notice