A Method for Systems Analysis and Specification with Performance, Cost and Reliability Requirements

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Abstract. In the past, space design activities mainly emphasized the system requirements. The available methods focused on functional aspects only. The cost was estimated at the end of the process. Recently, new design methodologies have been proposed. Among them, the design-to-cost (DTC) method was developed to include the cost as a parameter. In this work we propose an extension of the DTC method for systems analysis and specification. In other work we applied it to the design of a reaction wheel. Its basic components are described. General information on system development is related. The object-oriented approach is used as a modeling tool. Performance indexes are defined. A set of algebraic equations describes the cost behavior as a function of system parameters. Reliability is evaluated secondarily. The proposed model embodies many approaches to solve and/or optimize a problem with any level of complexity.

Keywords. Concurrent engineering, system engineering, design to cost method, reaction wheel.

1 Introduction

Reality shows that aspects not directly tied to the performance of equipments have equal or, in certain cases, greater role than the performance itself. This conducted to the development of design techniques in which aspects as cost became treated as design constraints, and not more as something to be evaluated at the end of it. This

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fact brought a reordering of priorities; and, in this new scheme, the performance obtained became the possible one that, even so, ensures the technical success of the mission, and not the desired one anymore, that could be unacceptable due to its cost [1-2].

In this work we present a method for systems analysis and specification with performance, cost and reliability requirements. In other work it is particularly applied to the reaction wheels destined to microsatellites, with emphasis in the electronic control system. It is desirable that actuators of such nature have the following characteristics of performance: high efficiency, low power, good dynamic response, long and useful life, and possibility of highly integrated implementation.

Besides the requirements of performance, the system shall also to satisfy criteria of cost and reliability , quantities usually evaluated after the conclusion of the project. For that, the method to be presented shall be an extension of the method known as “design-to-cost” (DTC) [3], where the requirements of performance and reliability are “negotiated” during the project as functions of the limitations previously imposed to its cost [4-5]. This work is the first part of a larger previous work [13].

2 Methods of Conception and Design of Systems

2.1 Phases of a project based on requirements (“Design-To-Requirements”-DTR)

NASA adopts a design cycle based in phases that organize the activities of a project in a logical sequence of steps [3, 6]. This systematic method defines a series of progressive steps with well defined goals that conducts to the realization of all objectives of the project. A summary of the project phases and their respective objectives is shown in Table 1. The activities in Pre-phase A, in Phase A and in Phase B are denominated phases of project formulation, since the emphasis is on requirements analysis, project planning, concept definition and demonstration of realization. Phase C, Phase D and Phase E are denominated phases of implementation because the operational software and hardware are designed, fabricated, integrated and put into operation.

Table 1 – The project cycle of NASA. Source: [3]

Project phases	Objectives
Pre-phase A: advanced studies	Preliminary requirements and conceptual analyses
Phase A: preliminary analysis	Definition of requirements and comparative studies
Phase B: definition	(B1) Definition of the conception and preliminary design (B2) Process of selection of service suppliers (if necessary)
Phase C: design	Final design and development
Phase D: development	Fabrication, integration, tests and evaluation
Phase E: operations	Pre-flight and in-flight operations

2.2 Method "Design-to-Cost" (DTC)

In the **method "design-to-requirements" - DTR** the resources are generally allocated in such a way to satisfy a set of functional specifications. This approach brings to several problems. The designers of subsystems tend to optimize the performance of its module instead of trying to optimize the performance of the project as a whole. Generally, they keep attention to the technical aspects, that results in a reduced exploration of the possible alternatives. So, the traditional mentality of matching requirements is a barrier against the continuous improvement and the reduction of costs [7].
The **method "design-to-cost" - DTC** searches to obtain the maximum return of a system maintaining its cost at levels previously determined (Figure 1). It consists in the choice of a set, maybe among many others, of technical parameters of perfor mance and attributes of design that represent an alternative capable of satisfying the objectives aimed by a system within a program and a range of costs [3].

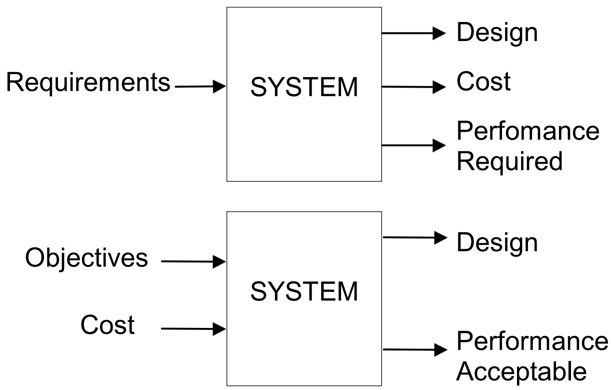

Figure 1 - Comparison of methods of design. Adapted from: [3].

The method DTC helps the project teams to take decisions based in more precise information on how the technical parameters of performance and attributes of design affect the cost.
Despite the method DTC may be regarded as a problem of optimization subject to constraints, its approach is not always done by conventional analytical or computational methods, since the functions that describe it are not, many times, possible to be found. Instead of this, it is up to the project teams to search and negotiate possible alternatives to build a system.
The model DTC is formed by the integration of various models and tools. They include: models of cost, models of performance of subsystems, models of reliability, and tools of analysis and decision.
The model DTC is primarily filled with equations and values of parameters that describe a preliminary implementation, the **base model**, common to the project teams. Initially, this model can only include basic and elementary descriptions of the project. The detailing increases in each phase, jointly with the understanding of the

designers. These details include technical information - typically mass, power and reliability, all related in a list of equipments - and equations of performance. The next step consists in establishing equations that show the inter-relations among variables of performance and **equations of cost**. The costs must be expressed by equations that reflect their relations with design attributes. The equations of cost must be structured in such a way that they can express gradients of cost – as the cost varies when attributes of performance are altered.

Once the base model is implemented , we can initiate the interactive process of system optimization. An increase of costs that violates the restrictions, brings the team to reject the proposed change or initiate a search for compensation in another subsystem. In this process, when an alternative implementation is found, it shall become the new base model.

Summarizing, the model DTC shall capture the objectives and knowledge of the system and the cost information associated, and shall be capable of doing reliable cost projections for alternate implementations. There resides the major difference with respect to the traditional methods of design. About the phase of implementation of the design, they follow the method DTR presented previously.

2.2.1 Modeling of Cost

The modeling of cost has been used to analyse the feasibility of a proposal. However, this use becomes inadequate to take decisions when treating complex systems. The modeling shall not have the objective of decision making on what or how we should do something. On the contrary, it shall give a deep comprehension of the methods used, data involved and it shall be sufficiently flexible to estimate the cost in all phases of a project.

The cost can figure as a parameter of engineering that varies with physical parameters, with technology and with methods of management.

Experience shows that models more refined than the specific cost (cost per unit mass) are needed. This brought to an estimation of costs using **parametric models**. These models are based on physical, technical and performance parameters. Starting from an **historical data base** we define coefficients and expressions that show how the cost of a system or subsystem varies as a function of the characteristic parameters.

Other adjustment factors correct uncertainties on the level of development of determined **technology**. The worst case occurs when new technologies are introduced with which the design teams have not any familiarity.

Another criteria refers to the **risk** of employment of a technology as a function of its **degree of qualification**. New technological resources tend to increment the cost when their use in special conditions is less determined.

An analysis of risks treats the uncertainties that can jeopardize the objectives of a system. Two sources are considered: uncertainty in the estimation of costs and growth of cost due to unexpected technical difficulties.

We use to approach all the mentioned criteria through an integrated analysis, called **Methodology of Concurrent Engineering**, where technical specialists and cost analysts cooperate in the mapping and interconnectivity of all points that affects the cost and the performance of a complex system. They rely on valid and flexible statistical analyses originated from models and data base updated with the advancement of the technology and the acquired experience [3, 8].

2.2.2 Considerations on Reliability

The cost of a fault depends on the instant it occurs, its scope and the available measures. The scope of a fault refers to its effect on the other components. Measures allow a rearrangement of command in such a way to minimize the consequences of a fault [3, 4, 9].

2.3 Extended Methodology Oriented to Objects (“Design-to-Objects” - DTO)

In the design oriented to objects (OO), the decomposition of a system is based on **objects**, the basic units in which a system is decomposed. It contrasts with **functional strategies**, where the basic units for decomposition are **functions**. In functional methods, each module represents a function or an operation that performs an activity in the system. In the approach oriented to objects a module is an object, which is not a functional entity that represents an operation, but an entity that represents some data in the system together with the operations that can be realized on the data during the activity of the system [10].

2.4 Method of Representation of Knowledge by Frames

The **“frames”** were introduced to permit the expression of the internal structures of the objects, maintaining the possibility of representing inheritances of properties as semantic networks. In general, a frame consists of a set of attributes that, through its values, describe characteristics of the object represented by the frame. The values given to these attributes can come from other frames, creating a network of dependence among the frames. The frames are also organized in a hierarchy of specialization, creating another dimension of dependence among them. The attributes also present properties that relate to the type of values and to the restrictions of numbers that can be associated to each attribute [11].

3 The Method Proposed

3.1 Introduction

The method presented here intends to provide elements that help the process of decision making during the entire cycle of a project. The analysis based in objects was inserted in this method for having a direct correspondence with physical elements that constitute the system, which makes it more clear and practical than a functional analysis. The objects are identified through information based on bibliographical searches, simulations and experimentations. The proposed tool presents two main parts **: a global analysis and a specific analysis**. The first one treats of an object to be acquired/designed as an unique element characterized by its attributes. The second one constitutes a refinement of such object.

3.2 Global Analysis

The most comfortable and certain situation to obtain a quality product is to acquire it from some manufacturer. The method presented in this section offers a solution to the question of choice of a product among other similars. Departing from a superior hierarchical level, a frame is built with a list of attributes of the product with information obtained from different companies. These attributes are then filled with values desirable for the realization of the objectives of the mission, resulting from a preliminary study. Such data constitute the initial **base model. Commercial models**, with characteristics similar to the base model, are then juxtaposed.

A comparative analysis shall determine which models available in the market are compatible with the necessities of the mission. For this, the values of the attributes are normalized (Equation 1). So, the nominal value of each attribute (*Vn*) of the commercial models can be expressed as a relative value (*Vr*) in relation to the value of the variable in the base model (*Vb*).

$$Vr = \frac{Vn}{Vb} \times 100 \qquad (1)$$

To indicate a variation or dispersion of the *n* relative values of a commercial model, except cost, around the base value, 100, it is defined a deviation given by Equation 2, inspired in the calcul of the standard deviation.

$$Desvio = \sqrt{\frac{\sum_{k=1}^{n} (Vr_k - 100)^2}{n}} \qquad (2)$$

We can also attribute a weighting factor f_k to each difference to express the relevance of a datum with respect to the others, according to the objectives of the project, according to Equation 3.

$$Desvio = \sqrt{\frac{\sum_{k=1}^{n} f_k (Vr_k - 100)^2}{n}} \qquad (3)$$

In this way, the greater the deviation of a commercial model, the greater will be its dissimilarities with respect to the ideal model.

The costs associated to each model are represented by a fraction 1/1000 of a monetary unit and are assumed invariant in time. the cost of the base model is a value previously stipulated that will serve as one of the parameters o acceptance of

the project. It is desirable to establish a level of tolerance above which the project is rejected immediately.
With this global analysis we intend to provide greater subsidies to the design teams in the choice of a system or other equivalent in a rapid and systematic way.

3.3 Specific Analysis

In discrepant cases or in the existence of limiting factors, as cost for example, the reliability of partial or total realization/acquisition of the object can be analysed with greater rigor by partitioning it in smaller objects. The refinement in the base model will furnish data for a new comparison. Having as reference the base model, we proceed with the identification of the objects that constitute the system and the disposition of the attributes of these objects in frames. Over the attributes are defined concepts and indexes for evaluation of performance, cost and reliability of these inferior objects and, therefore, of the product in question. All these parameters are related in such a way that the system can be evaluated and optimized. Since the attributes of the smaller objects do not have the same values as the base model, they pass to constitute the **current model**. The current model presents the same attributes of the base model, despite with distinct values. Their values are filled as soon as the inferior objects are built.

3.3.1 Frames of the Inferior Objects

In this step the main objects of the system are explicated through their respective frames. The quantity and specificity of the selected objects depend on the design team. The attributes can be expressed as quantitative or qualitative variables. To each value of an attribute is associated a numerical concept, *C*. This concept is attributed by an specialist (example in Table 1). The function of this concept is to characterize the attributes given to the objectives of the system. The numerical range adopted for the representation of concepts expresses the level of knowledge of the specialist on the object in question.

Table 2 – Shapeof the frame of a generical object

Attributes	Units	Value	Concept
Attribute A	cgs	1,7	5
Attribute B	-	bom	3
Attribute C	mks	3000	2

3.3.2 Correlation

The information on the influence that each attribute exerts on other is expressed in the matricidal form. This table substitutes analytical expressions, that are, many times, of difficult obtention. It is formed by the contiguous disposition of the attributes of the objects, as a model presented in Table 2. The cell correspondent to a pair (attribute-row, attribute-column) is filled with a value, the degree of correlation, that express the relation among them. The degree of correlation (*r*) adopted is designated by an integer number belonging to an interval previously specified. In the same way, this range is a function of the knowledge of the specialist. The matrix formed is symmetrical in relation to the main diagonal. The elements of this diagonal are considered null, reflecting trivial correlations.

Table 3 – Correlations among attributes of objects

			Object	
		Attribute A	Attribute B	Attribute C
Object	Attribute A	0	1	3
	Attribute B	1	0	5
	Attribute C	3	5	0

3.3.3 Evaluation of Performance

The performance of the system can be evaluated by many modes. In all situations we desire an index of easy obtention that characterize the actual state of the system and that serve as a basis for the processo of refinement of it. For the present case two indexes are proposed: **the index of coupling (α) and the index of performance (η).** These indices make use of the concepts of the attributes and of the correlations among them.

The index of coupling of the i-th attribute is defined as the arithmetical mean of the *n* degrees of correlation referred to it. That is,

$$\alpha i = \frac{\sum_{j=1}^{n} rij}{n} \qquad (4)$$

The index of performance of i-th attribute is given by:

$$\eta i = \frac{\sum_{j=1}^{n} C_j^2 . rij}{n} \qquad (5)$$

where C_j is the concept of the j-th attribute. The form of expression 5 was defined in function of the limits of the ranges adopted for the concepts of the attributes and the degrees of correlation.

The index of coupling expresses a correlation of an attribute in relation to the others. In this way, when comparing the concept of an attribute with its index of coupling, we can evaluate whether or not the resources expended with it are really necessary for a satisfactory performance of the system. Whereas the index of performance shows the balance between the concept and the relevance of an attribute in relation to the superior object. These relative indexes can be used in comparisons among different alternatives of a design.

3.3.4 Estimative of Cost

The cost of a project is a function of many factors.The cost of an object is obtained by expressions whose parameters are one or more of its attributes. Then it is a parametric model of cost, formed by mathematical equations that relate the cost to physical and performance parameters. Its application is limited to a pre-defined range of values. Here the costs are also expressed by a fraction of the monetary unit and considered invariant in time. The total cost is given by the weighted sum of the estimated costs of each object of the system. Two factors of adjustment of cost are inserted to correct uncertainties on the familiarity of the design team and the technological qualification of the object in question. These adjustement factors are presented in Tables 3 and 4 and are based in [3]. There is no a formal relation among the units in which the parameters are given and the unit of cost. Costs of design, integration and tests shall be included in the model. The complexity of the model is reduced when the attributes of greater relevance of the system are used as parameters in the equations. We propose that the attributes chosen to represent the cost of each object be extracted among those that possess the greater indexes of coupling. The forms of equations are purely empirical. Their coefficients are given by an statistical analysis based in studies of cases already conducted.

Table 4 - Factors of adjustment of cost according to the level of knowledge of the team. Adapted from [3]

Level of knowledge of the team	Factor of adjustment
The team is totally familiar with the project and already completed many identical projects.	0,7
The team has much familiarity with the type of project and realized similar projects.	0,9
The team has experience in similar projects but not identical.	1,0
The project introduces many aspects with which the team does not have familiarity.	1,2
The team does not have any familiarity with this type of project.	1,5

Table 5 - Factors of adjustment of cost according to the degree of technological qualification of the system. Adapted from [3]

Degree of technological qualification	Factor of adjustment
The system is used largely in identical applications.	0,90
The system is already in similar applications.	1,00
The technology proposed is recent and only engineering models use it.	1,05
The system is qualified in tests performed in controlled environments.	1,15
The technology employed is new and no test was performed.	1,20

Upon varying the parameters of the system, the cost also alters. To relate such percentage variations the concept of sensitivity is introduced. **The sensitivity (S) of the cost of an object (c) in relation to a given attribute (λ)** is given by Equation 3.6, according to [12]:

$$S_{\lambda}^{c} = \frac{\partial c}{\partial \lambda}\frac{\lambda}{c} \qquad (3.6)$$

In this way, the value of S can be used to determine a change per unit in c due to a change per unit in λ. For example, if the sensitivity of cost relative to an attribute is 5, then an increase of 1% in λ results in an increase of 5% in the value of c.

3.3.5 Reliability

The model of rate of faults of an object is obtained with the manufacturer or obtained experimentally. The expectation of the useful life of a system is fundamentally determined by the environmental conditions of use and by its topology. The investment on the planning of quality can contribute to obtain a reliable system and with minimal redundancy, that can diminish the cost of production.

The reliability was inserted in the proposed model as an attribute: the useful life of each object. Despite this concept is not adequate for electronic systems, it was chosen by a question of uniformization. The matrix of correlations determines which are the parameters that have some relation with the useful life of the object. Starting from that, the phases of project and test can be better planned.

3.3.6 Actualization of the Current Model

Starting from the frames of the objects formed and the tables of performance, cost and reliability, the current model is structured. The attributes of the current model are extracted directly from the attributes of the smaller object or obtained through simulations and/or experimentations with the data of these objects. Having one or more candidates to current model resulting from the specific analysis, we shall submit them to a global analysis to select a new base model. The function of this procedure is not to provide a definitive answer, but to clarify doubts, arise questions and point possible solutions.

The procedures described in the specific analysis shall not necessarily be followed in the order presented. The flexibility of the model implemented shall permit alterations a any instant. The interactivity shall be always valued.

4. Conclusions

In this work it was presented a method for the analysis ans specification of systems with requirements of performance and cost, according to the model DTC. This method was then applied to reaction wheels in other paper. A flexible tool was proposed that aggregates different modes of treatment and modeling of complex systems with the same objectives. It is capable of assembling information of diverse kinds and treat them globally. As other methodologies, presents advantages and disadvantages. The initial implementation can be difficult, either by financial, organizational or human questions. Due to this, in this work were related the most different approaches and used parts of what is of best among them, without deepening the concepts involved. This work is the first part of a larger previous work [13].

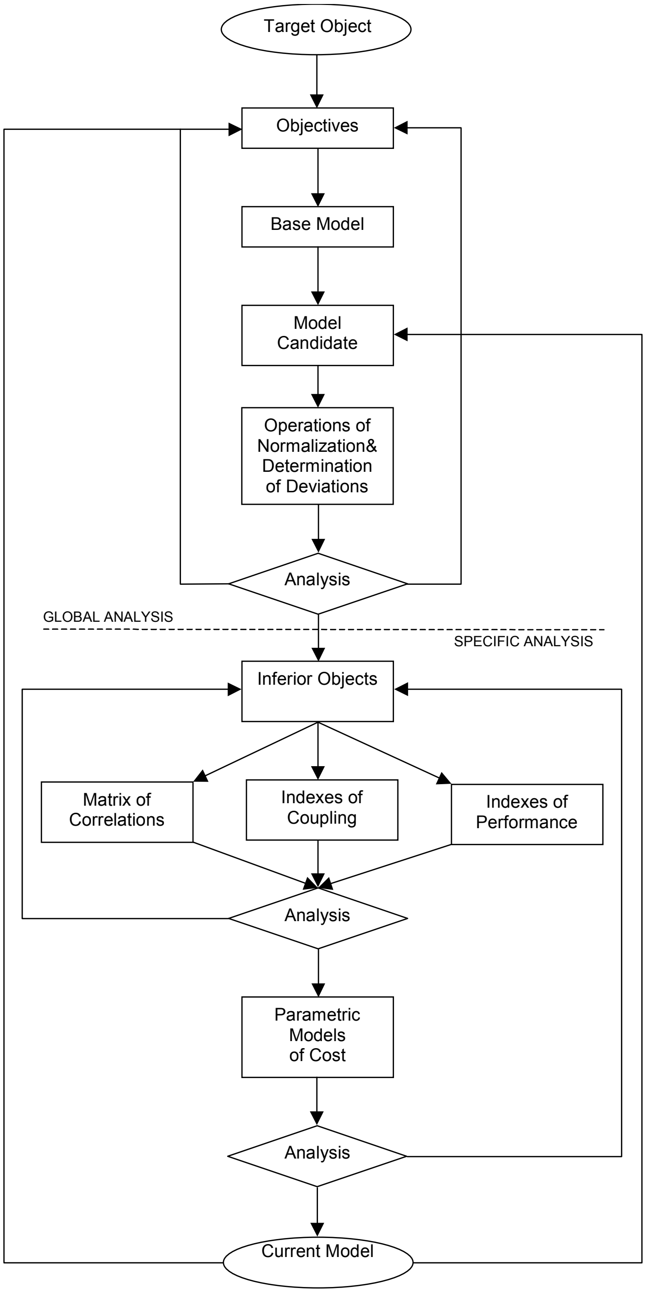

Figure 2- Conceptual flow graph of the method presented.

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