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Design for Autonomy: An Integrated Product Development Tool for Reengineering of Complex Products for the Brazilian Space Sector

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Abstract. This paper presents the integrated product development tool Design for Autonomy for reengineering of foreign complex products. Design for Autonomy is a new member of the Design for X family, which aims at integrating the requirements from the X area, in this case autonomy, into the conceptual phase of the product development process. This tool regards to decision making activities and their outcomes: decisions about the interrelations with the design of products. The objective of Design for Autonomy is to assure that the product can be designed, produced and operated in Brazil for a defined period of time at a minimum risk of being dependent on export bans or unavailability of components. This can be accomplished by the Design for Autonomy model comprising four steps: (1) An analysis to identify critical elements and means for achieving their technological domain; (2) Preparation of nationalization; (3) Reverse engineering of the original product in order to obtain the technological know-how; and (4) Forward engineering including the adaptation for the new environment in Brazil, stimulating improvements and added value. In a pilot project, the Design for Autonomy tool is being successfully applied to the development of a Brazilian thrust vector control system, a subsystem used for attitude control of satellite launch vehicles. The technology originates from the German Aerospace Center (DLR) and is transferred to the Brazilian Institute of Aeronautics and Space (DCTA/IAE).

Keywords. Integrated product development, Design for X, Design for Autonomy

Introduction

Brazil has a high technological dependence of space technologies, compared to other space fairing nations like India, Japan or China who have high level of priority for full independence of technologies. In the past, the Chinese and Indian space programs have been compromised by international markets for space technologies and thus, have built up strong domestic capacities [1].

Another example is Japan, which only undertakes a space mission if it can be assured that Japan is able to launch its spacecraft. Japanese governmental satellites have never been launched by foreign launch service providers [1]. History shows that,

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besides Germany, all countries looking for rocket technology used technology transfer for achieving national domain typically with the following four steps: (1) Procurement/proliferation; (2) Reproduction under license; (3) Performance advancements; and (4) Own development [2]. Technology transfer strongly depends on the culture, organization, politics, human infrastructure, and availability of components that are dominant inside the new environment. It is a common faulty assumption that a system, technology or a process works without major problems in a different context or in a new environment. Transferees are obliged to match the functions and assimilate, adapt and improve upon the original technology [3]. This paper introduces an integrated product development tool nominated Design for Autonomy to nationalize strategic technologies applied, embedded or implemented within a product.

1. Design for Autonomy

The Design for Autonomy tool is a new member of the DFX family, developed on basis of the DFX shell [4]. The term *autonomy* can be rendered as self-rule or self-determination and is used in this context as freedom from external control or influence. Design for Autonomy refers to the processes necessary for the successful nationalization of strategic technologies applied, embedded or implemented within a product which is realized via reengineering. The model of Design for Autonomy is depicted in Figure 1. The first activity of the product development process, the 1st step, is the modeling of the product for further analysis including the identification of critical elements of the product. The nationalization of the product is being prepared in the 2nd step. Having a prepared product/technology as well as a prepared environment for nationalization, reengineering is carried out in order to obtain a national product (3rd and 4th step).

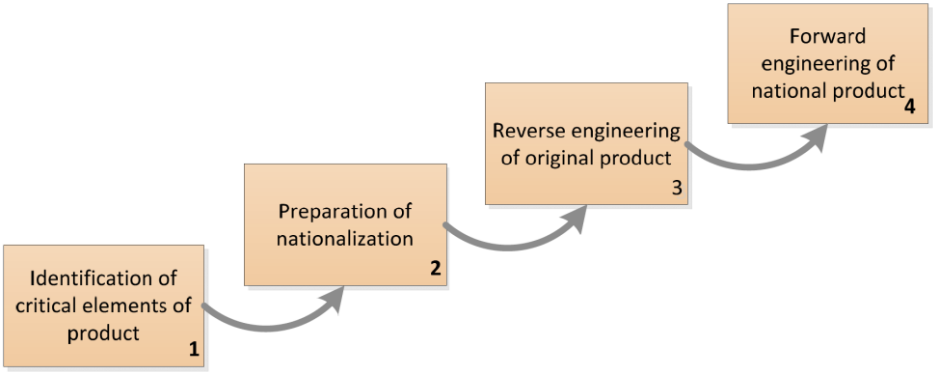

Figure 1. Model of Design for Autonomy consisting of four steps.

The process of reengineering is illustrated in Figure 2 and initiates with reverse engineering, an analysis of the original product that includes design recovery originating from the implementation phase and the design phase, restructuring the requirements of the system (data-to-data) and the design (graphical and functional).

The second part of the reengineering process, the forward engineering, continues with the definition of new and modified requirements. New national designs are created in order to achieve the development of a national product. The term *forward* is necessary to implement in order to distinguish this process from reverse engineering.

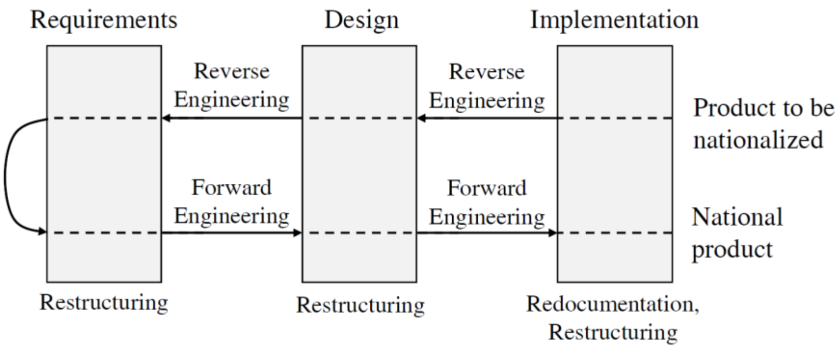

Figure 2. Relationship between the terms of Forward-, Reverse- and Reengineering represented by life-cycle phases, after Chikofsky and Cross [5].

Design for Autonomy is part of a comprehensive systematic strategy for nationalization of foreign technologies which is called Technology Nationalization Framework (TNF) [6]. This framework comprises the identification of strategic technologies in Brazil and gives support for the decision making process for their nationalization. An evaluation of feasibility for development of national domain and subsequently its coordination and cooperation helps to stimulate the best use of resources and competencies available in Brazil. Intellectual property related questions are part of TNF prior to the application of the Design for Autonomy tool.

In the following, the processes of the four steps of Design for Autonomy are presented in detail, using a function modeling methodology based on IDEF0. Each function or activity of the respective step is placed in a box, identified with a number at the bottom right. Inputs are represented by arrows entering the left side, outputs by arrows exiting the right side. Control/management is represented by arrows entering the top of the box and mechanisms/processes by arrows entering from the bottom of the box.

1.1. The 1st step - Identification of critical elements

The activity of the 1st step, the identification of critical elements, is illustrated in Figure 3. This first step is required in order to analyze the product to be nationalized, to adequately represent the product for further design decisions, and to collect and categorize product information. In case of identification of high critical elements, action lists are generated in order to obtain technological domain. Not identified critical elements may hinder or impede the product development process or may result in project delays or excessive cost. This activity is the initial step of the Design for Autonomy tool, breaking down a complex product into manageable elements which are being identified.

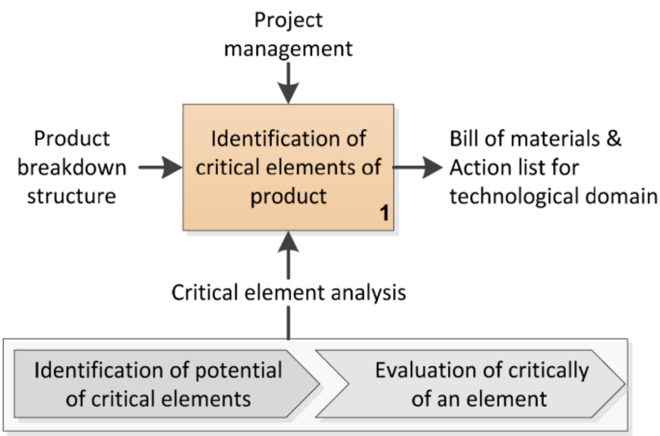

Figure 3. 1st step of Design for Autonomy: Identification of critical elements of product.

1.1.1. Modeling for product analysis

According to Huang et al. [4], the product modeling can be characterized into three general categories of product information, namely, composition, configuration, and characteristics. The composition of what the product consists of is allocated into the Product Breakdown Structure (PBS), a technical tree which is a structured representation of all various elements of a system [7]. A PBS is a hierarchical structure of the complete set of physical systems and subsystems including operational system, training system, development support, production support and so on, which identifies the configuration items [8]. It hierarchically details the elements, or physical components of the respective product beginning with the final product at the top of the hierarchy, breaking down a complex product into manageable elements. The PBS also includes non-exhaustively the configuration of the product, defining the relations between the elements.

Further information of the configuration and the key characteristics of the elements for the Design for Autonomy tool are included in the bill of materials, represented in Table 1. Besides the standard entries (hierarchical level, part number (PN), revision, description, quantity and unit), the criticality of the elements and a make, buy or make and buy decision is added.

Table 1. Sample for bill of materials.

Level					PN / Specification	Rev.	Description	QTY	Unit	Criticality of element	Make, buy
0	1	2	3	4							

1.1.2. Mechanism of identification of critically of elements

In a first stage, it is assessed if the respective element has a potential to be critical for the development of a national product. Therefore, the questionnaire is applied to define: (A) if the element is relevant for the product, and (B) if this elements requires development of technology. A potentially critical element will be diagnosed if the respective element obtains at least one 'yes' in both categories (A) and (B). This first evaluation is based on the TRA Deskbook [9] and was adapted by the Brazilian Center for Strategic Studies and Management in Science, Technology and Innovation (CGEE) [10].

In a second stage, the criticality of an element is determined, which is executed for those elements that are marked as potentially critical elements. The flow chart for evaluation is depicted in Figure 4, which is based on the InsightTec tool from CGEE [10]. For the input, the following information of an element to be evaluated is required: manufacturer, manufacturing country, majority shareholder of manufacturing company, and export restrictions from

1. respective national institutions (e.g. from Export Administration Regulations (EAR), International Traffic in Arms Regulations (ITAR) and Treasury Department's Office of Foreign Assets Control (OFAC) for US goods or Federal Office for Economic Affairs and Export Control (BAFA) for German goods), and
2. multilateral export control regimes (e.g. Missile Technology Control Regime (MTCR) [11] or the European Council (EC) Regulation No. 428/2009 [12]).

Four different categories of criticality can be obtained from the evaluation which are defined as:

- Non-critical element: No short or long term restrictions for acquisition or production of element in Brazil; sufficient alternatives available.
- Low-critical element: Long term availability for a specific element with limited acquisition resources in Brazil or unlimited acquisition resources out of Brazil assured.
- Medium-critical element: No long term availability assured and uncertainty of future acquisition or unlimited acquisition resources for a restricted element in foreign country. Furthermore, an element on critical project pass may be classified as medium-critical element.
- High-critical element: Restricted access or difficulties in acquisition and availability for identified element.

The availability of elements is characterized by three different stages, namely:

1. Independence - The required technology is/was developed and the element is produced in Brazil,
2. Non-dependence - Brazil has free, unrestricted access to the element and its technology, and
3. Dependence - Brazil has restricted access for acquisition of the element.

Annotation: The definitions used herein are adapted from the EC-ESA-EDA workshops on Critical Space Technologies for European Strategic Non-Dependence [13].

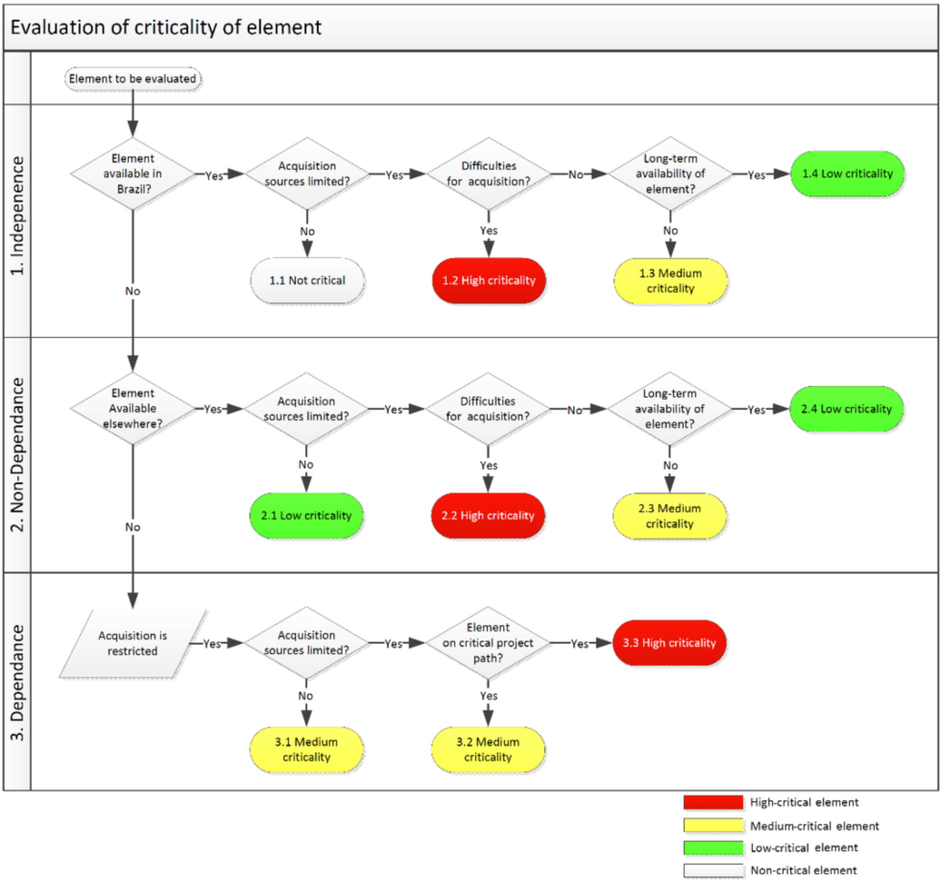

Figure 4. Determination of critically of elements, after ESA [14] and CGEE [10].

1.2. The 2nd step - Preparation of nationalization

The acquired data from the first step is necessary to prepare the nationalization. The second step, depicted in Figure 5, involves specific preparations for the product itself and preparation of the setting in order to generate an adequate and prepared environment for the nationalization. The product specific preparation provides insight into the national and international industry for the product and its elements, including the possible critical elements. Furthermore, a research of possible patents avoids the violation of international laws and the national and international research review gives an overview of the state-of-the-art. The preparation of the product setting includes the creation of an organizational structure for the Product Development Process (PDP) and the modification and adaptation of the necessary infrastructure and training. According to Andreasen and Hein [15], development projects require a separate organization since a range of activities does not fit into the existing pattern of the basic (external) organization. An *internal* organization is made up of work, project management and executive elements, whereas the *external* project organization acts as technical reference and supplier.

The preparation of nationalization is a continuous process that not necessarily has to be concluded before initiating the next steps. Efforts especially for the product specific preparation and the adaption of the infrastructure should be ongoing until the end of the product development to ensure the conservation of the *status quo* of a prepared environment.

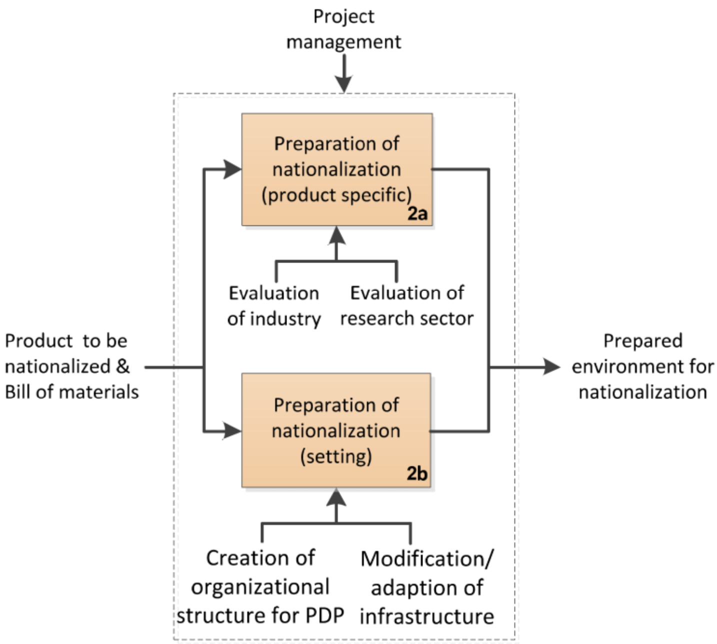

Figure 5. 2nd step of Design for Autonomy: Preparation for nationalization.

1.3. The 3rd step - Reverse engineering of original product

Reverse engineering of the original product, the first activity of reengineering depicted in Figure 6, aims to analyze and examine the product in order to identify its components and their interrelationships and to obtain the know-how and know-why. This knowledge is necessary in order to continue reengineering with the second activity, forward engineering to redesign a national product.

The activity of reverse engineering of the original product includes four tasks:

1. Procurement - The original product or at least a large part of it has to be acquired and imported from the transferor according to the bi-national contracts.
2. Assembly and integration - The original product has to be assembled and integrated in national laboratories with the adequate equipment and infrastructure.
3. Functional testing - Functional testing, if possible with technical staff and/or support from transferor, has to be accomplished in order to train the team and assure save handling and use, and to understand form and functionality of components and their interrelationships.
4. System identification and modeling - This task is case specific and depends on the product to be reengineered.

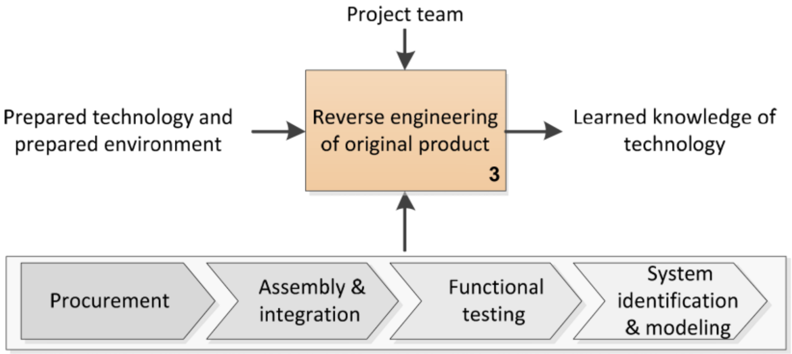

Figure 6. 3rd step of Design for Autonomy: Reverse engineering of original technology.

The reverse engineering has to be documented adequately in order to facilitate the forward engineering of a national product.

As an example for the reverse engineering, in Figure 7 the engineering model of the actuation system for the thrust vector control system at the transferor is depicted and in Figure 8 the national reverse engineered model. Based on the lessons learned from the transferor, the development of Brazilian engineering model prevented possible defects and shortened the development time, saved money and brought improvements upon the original model. This task revealed characteristics of the actuator like functional principles, dimensioning and effective areas of piston. The gained knowledge brought ideas for possible weight savings and performance gains.

Figure 7. Engineering model of actuation system at transferor.

Figure 8. Reverse engineered model of actuation system in Brazil.

1.4. The 4th step - Forward engineering of national product

The second activity of reengineering is forward engineering, depicted in Figure 9, using the gained knowledge from the reverse engineering activity. This step leads to the development of a product with national domain, reducing the risk of being dependent on export bans or unavailability of components. Furthermore, the knowledge of the original technology and the identification of its strengths and weaknesses give the opportunity for product enhancements, leading to innovation and added value.

The reverse engineering from the 3rd step brought knowledge of the design and requirements of the original technology. For the development of a national product, the original requirements get restructured, thus changed, modified or maintained and a new specification is obtained. With this new specification the designs get reviewed and if necessary changed or modified for the national product. The redocumentation assures a consistent technical documentation of the national product. Therefore, the available documentation of the transferor is reviewed, adapted, changed or modified and converted to the national layout, norms and standards.

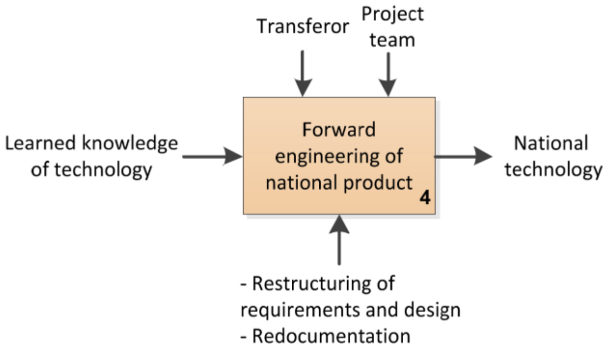

Figure 9. 4th step of Design for Autonomy: Adaptation for new environment.

The reverse engineering of the acquired actuator from the technology transferor together with the obtained knowledge from the actuators purchased for different applications and available literature for actuation systems lead to the forward engineering of Brazilian actuator engineering and qualification models, as illustrated in Figure 10.

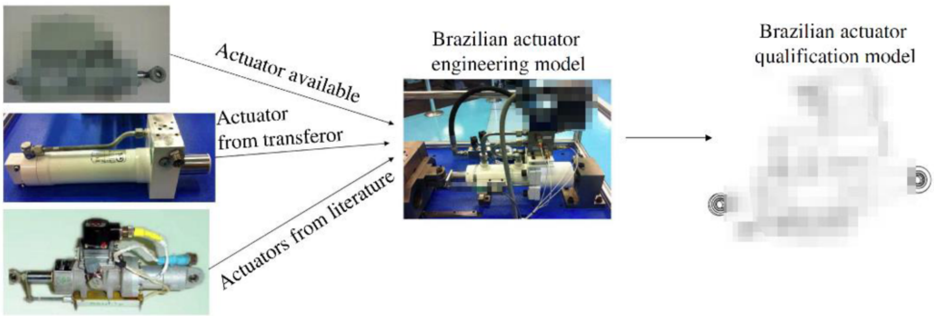

Figure 10. Flow of knowledge for forward engineering of Brazilian actuator engineering and qualification models.

2. Discussion

Like any manufactured product, the Design for Autonomy tool is set to be improved. In the pilot project for the development of a Brazilian Thrust Vector Control system, a right first time could be accomplished so far. Feasibility and the right focus of attention could be demonstrated by a balance between functionality and operability. However, validation is not a step that can be skipped and the tool has to be tested on a number of case studies for validation purposes. Design for Autonomy was being developed with the focus on the space sector in Brazil. Certainly, this tool and its processes may be adapted and adopted to other sectors / production industries in Brazil.

3. Conclusion

The integrated product development tool Design for Autonomy was introduced in this paper as part of the Technology Nationalization Framework for nationalization through reengineering of foreign high technology products. The application of Design for Autonomy fosters innovation and competitiveness in Brazil and ensures non-dependence of strategic technologies and products. Design for Autonomy is a balance between completely domestic/national development with intrinsically high cost, lead time and risk, and blind implementation of reverse engineering with risk of failure, more expensive solutions and/or higher vulnerability to embargoes. It includes product analysis of critical elements in order to not enter into a fatal spiral of total nationalization, where 100% of product has to be national. It represents a balanced development of reverse engineering that provides observations beyond those perceived by the original designer, creating an innovative scenario for straight forward engineering in order to prevent errors, save time and money and add value to the new national product. Design for Autonomy is a decision and design supporting tool that copes with high complexity and generates alternative views for a robust national design. The Design for Autonomy tool was successfully developed and applied within the Brazilian space sector, however, may be adapted and adopted to other sectors / production industries in Brazil.

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