System concurrent engineering of a mobile TT&C ground station for an unmanned aerial vehicle

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Abstract: This paper presents a system concurrent engineering approach for the development of a mobile Telemetry, Tracking and Control (TT&C) ground station for an Unmanned Aerial Vehicle (UAV). Traditional approaches focus on the product, development organization and the product concepts of operation (CONOPS). In those approaches the overall view of the inherent complexity in the development of a product, its life cycle processes and their performing organizations are not taken into consideration. The system concurrent engineering performs, simultaneously, stakeholder analysis, requirements analysis, functional analysis and implementation architecture analysis for the product, its life cycle processes and their performing organization. From the analysis, requirements and attributes are captured for the product, its life cycle processes organization and the relationships between them are identified. We have concluded that the impact, traceability and hierarchy links promote the anticipation of the life cycle process requirements to the early stages of systems architecting. Late changes are avoided and development costs are dramatically reduced, while satisfaction of stakeholders over the product life cycle is increased.

Keywords: systems concurrent engineering, systems engineering, concurrent engineering, complex product, integrated product development.

1. Introduction

Major investments into TT&C equipment took place a long time ago. Spare parts and service for all major components of the existing stations are not available anymore due to equipment wearing and technological evolution. An urgent need for the future will be a highly flexible multi-purpose mobile command, tracking and data receiving station. This new generation of stations must be highly mobile, automatic, and flexible in order to fulfill the new requirements of the aerospace market. The high mobility implies that their transportation and set up should be fast and easy with as less additional services as possible. The required operational effort will be reduced in comparison with today's standard if the new generation of stations supports automation during preparation and the operation itself. The high flexibility allows an easy and fast setup of the station for a specific mission.

Considering the requirements for the station new generation and using the system concurrent engineering approach, a case study was developed for a mobile TT&C ground station to track, monitor and command an UAV (Unmanned Aerial Vehicle) for missions of the territory recognition in a perimeter of a hundred kilometer.

This paper aims to present the system concurrent engineering approach for the development of a mobile TT&C ground station for an UAV. The approach is different from traditional systems engineering approach because it anticipates to the early stages of system architecting the product life cycle process requirements. It proposes to simultaneously develop, from the outset, the product and its life cycle processes performing organizations.

The paper is organized as following: Section 2 presents the traditional systems engineering and concurrent engineering approaches. Section 3 presents the systems concurrent engineering approach framework and method. Section 4 presents the models derived for the mobile TT&C ground station for an UAV using the approach. Section 5 discusses the advantages and opportunities for improving the proposed approach. Section 6 concludes this paper.

2. Traditional and concurrent system engineering

Mobile TT&C ground station products are complex. They are multidisciplinary products involving campaign planning, team organization, transportation, mission operations; analysis and reports. They must cope with extreme environmental conditions over their life cycle (salt, pollutants, contaminants, assembly and disassembly, temperature range, electromagnetic interference and compatibility) and they must undergo very strict calibration and tuning procedures. There are many opportunities to improve productivity over mobile TT&C station life cycle if a concurrent engineering approach takes place from the beginning of the station architecting stage.

Traditional systems engineering approaches do not provide an overall view of the system during its various life cycle processes. They focus on an operational product development starting from product concept of operations. They also focus on the development organization that must be put in place in order to assure that the product meets its operational requirements (ELECTRONIC...,1997; EUROPEAN..., 2009; INSTITUTE..., 2005; NATIONAL..., 2007). A product has life cycle processes other than operations and it must be recognized from the outset in order to promote gains in productivity in the product development organization, by the avoidance of late changes, and in other product life cycle process organizations, as the product will be developed taking into consideration their requirements. Life cycle process organizations themselves can be developed simultaneously to product development, when they are part of the scope of the whole product development effort.

For example NASA systems engineering handbook (NATIONAL..., 2007) states that systems engineering focuses in the development and the realization of a final product. Modern commercial standards, such as EIA 632 (ELECTRONIC..., 1997), state that systems engineering focuses on the operations product and on capturing requirements for the other product life cycle processes. In other words, these requirements are captured not to impact product development. The product will be systems engineered with operations in mind. When its architecture (and maybe detailed design) is defined, then life cycle processes requirements are captured to be implemented in life cycle process performing organizations. This paper proposes a method to take into consideration the impact of these organizations on the product during the product architecting process.

Conceptually, concurrent engineering acknowledges benefits of anticipating life cycle process requirements to the early stages of product development. For mobile TT&C station products, these early stages are the system architecting phases. A systems approach requires life cycle process requirements to be balanced in the beginning of the product development process. Concurrent engineering, however, in practice, treats life cycle processes separately and optimizes product design seeking each life cycle process productivity increase. For example, DFA optimizes for assemblability, QFD, for customer satisfaction, DFI, for inspectability, and so on.

Also, concurrent engineering is, in practice, applied to parts design and not to systems composed of many integrated parts (HUANG, 1996). This paper proposes how the concurrent engineering concept can be used for systems engineering.

3. The systems concurrent engineering approach

Hitchins (1996) states that complexity can be understood by what he calls complexity factors. They are variety, connectedness and disorder. Variety accounts for the number of different elements you have in a set. Regarding products, variety refers, for example, to the number of different parts a product may have, number of different functions it accomplishes, number of different requirements categories it is supposed to meet, number of different stakeholders it should satisfy. Connectedness refers to the relationships among elements. For example, how parts interact, how functions affect one another, how requirements conflict to each other, how value flow among stakeholders. Disorder refers to the level of tangling of those relationships. For example, is there a structure pattern for deploying stakeholder requirements through functional concept up to implementation architecture?

Figure 1 presents a framework to address complexity in product development –the total view framework evolved from Loureiro (1999). It has three dimensions. Each dimension addresses one of the complexity factors mentioned above. The analysis dimension addresses the variety factor. Along the analysis dimension, it is deployed what must be analysed in order to develop a complex product. A systems engineering process consists of stakeholder analysis, requirements analysis, functional analysis and implementation or physical analysis. The integration dimension addresses the connectedness factor. It defines what must be integrated along an integrated product development process: product elements and organization elements. Organization here refers to the organizations that perform product life cycle processes. Product elements and organization elements are the system elements. The structure dimension addresses the disorder factor. According to Alexander (1964) all structures evolve into an hierarchy. System breakdown structures are also represented in hierarchies.

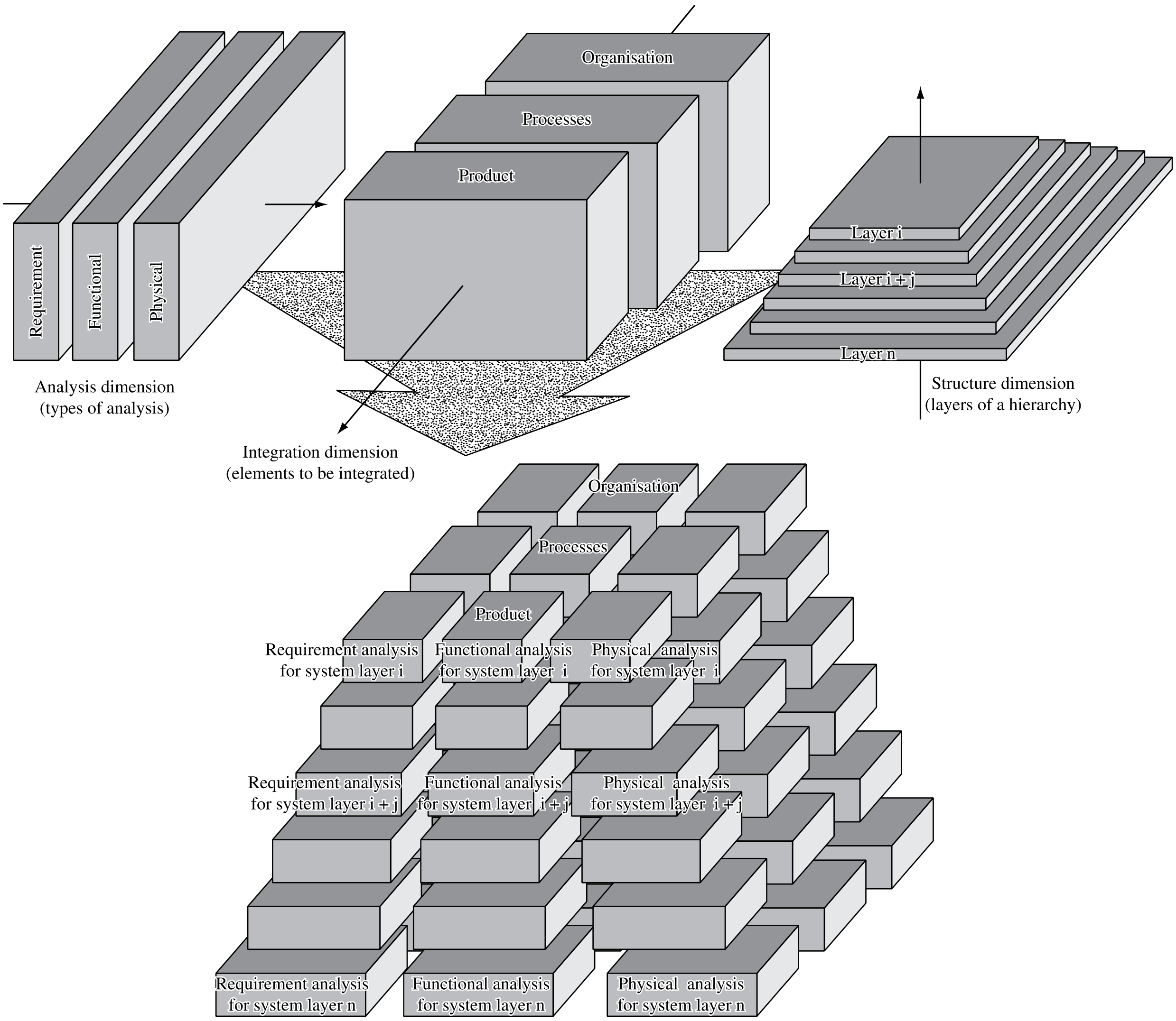

Figure 1. A framework to address complexity in complex product development – the total view framework.

Figure 2 provides an overview of a method within the total view framework. The method is called concurrent structured analysis method evolved from Loureiro (1999). Stakeholder analysis, requirements analysis, functional analysis and implementation (or physical) analysis is performed, simultaneously, for the product under development and its life cycle process performing organizations. The analysis processes are performed at each layer of the system breakdown structure. For example, if a car is the product under development, the analysis processes are performed at the car layer, at the power train layer, at the engine layer and so on.

Figure 3 details the concurrent structured analysis method showing how to incorporate the concurrent engineering concept in the systems engineering process.

The steps of the system concurrent engineering method are the following:

- Step 1: Identify the product mission, the product life cycle processes and their scenarios and, the scope of the development effort. Product mission refers to the product purpose or reason of being. Life cycle process scenarios are the alternatives in each process (for example, preventive or corrective maintenance) or the decomposition of a process (for example, advanced technology development, process engineering as components of the development process). The scope of the development effort consists of the life cycle processes or their scenarios that the development organization is also responsible for accomplishing. For example, EMBRAER is responsible for developing aircraft but is also responsible for providing maintenance services.
- Step 2: Identify product stakeholders and their concerns for each product life cycle process scenario.

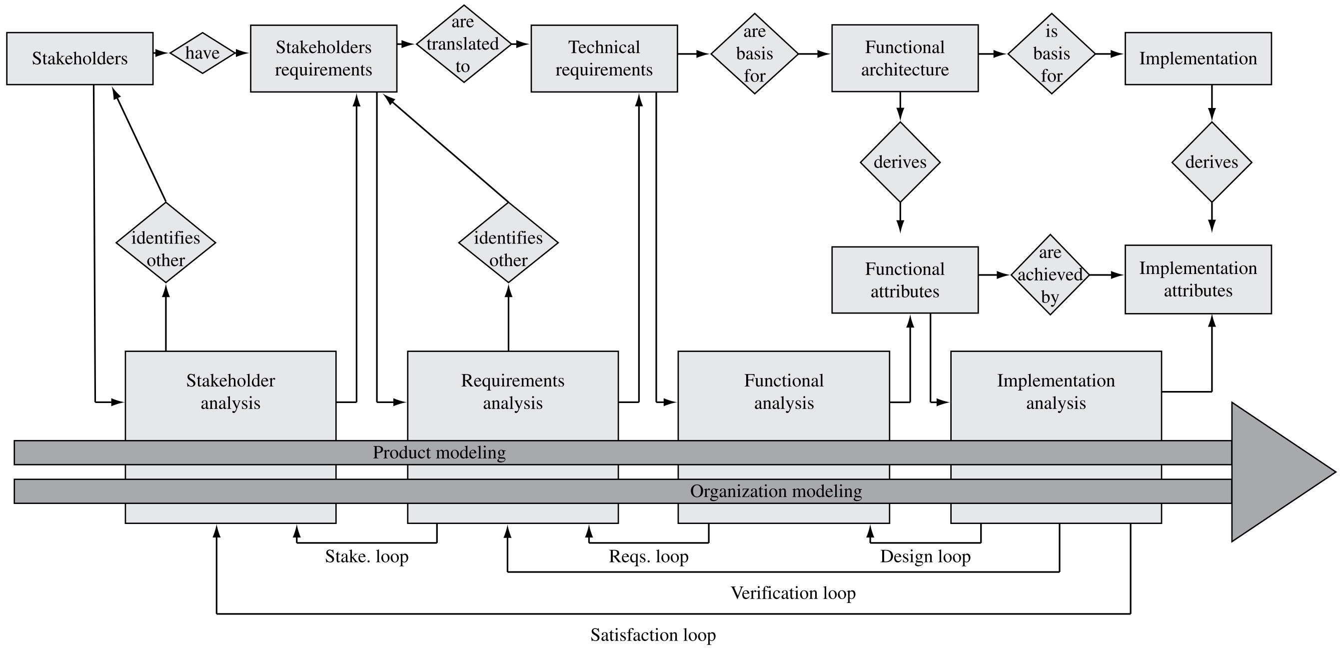

Figure 2. A method within the total view framework – the concurrent structured analysis Method.

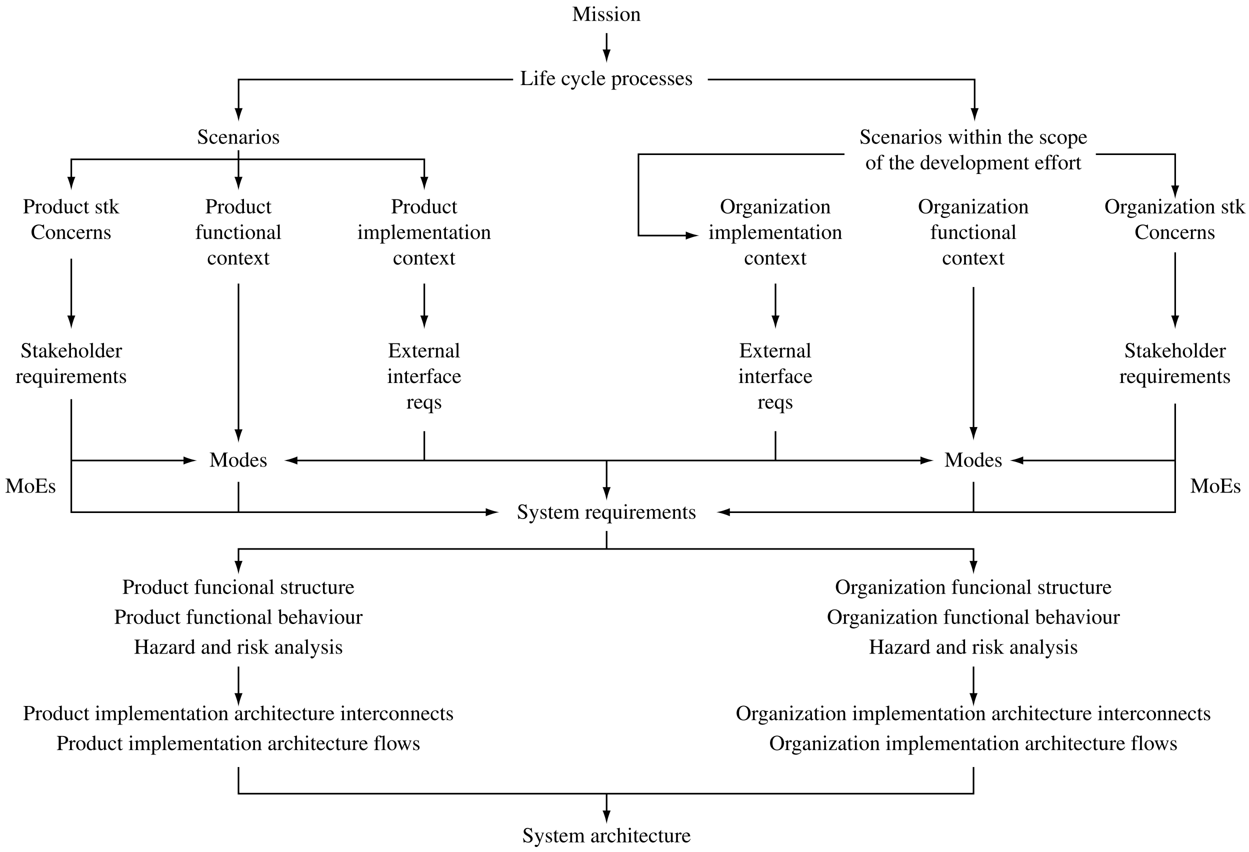

Figure 3. The system concurrent engineering method in detail (Source: LOUREIRO, 2010).

Product stakeholders are the people who affect or are affected by the product during its life cycle. Product stakeholders are identified per life cycle process scenario. Identify organization stakeholders and their concerns for each process within the scope of the development effort. Organization stakeholders are the people who affect or are affected by the business of the organization in question. Organization stakeholders are identified per life cycle process scenario within the scope of the development effort. From stakeholder concerns, stakeholder requirements are identified and measures of effectiveness (MoEs) are derived. MoEs must measure how the system meets the stakeholder requirements. From stakeholder requirements, functions, performance and conditions are identified. The definition of what functions the system will perform, how well the system is going to perform such functions and under which conditions comprise the requirements analysis process. Requirement analysis transforms stakeholder requirements into system requirements. System requirements will be met not only by product elements but also by organization elements.

- Step 3: Identify functional context for product at each life cycle process scenario and for organization at each life cycle process scenario within the scope of the development effort. Functional context defines the function performed by the system element and identifies the elements in the environment of the system. The environment of the system contains the elements outside the system function scope and that exchanges material, information and energy flows with the system. Those flows define logical interface requirements. Environment elements may have different relevant states. Sets of environment element states are called circumstances. The system must have different modes depending on the circumstances. Behavior modeling is required to show under which conditions system mode and system state transition occurs. Functions are identified per mode.

Functions are identified from outside in by identifying which responses the system is supposed to give to deal with each stimulus provided by the environment elements. For each function, performance requirements are identified.

Circumstances, flows between the system and the environment and function failures are sources of hazards. Risk analysis is performed on each identified potential hazard and exception handling functions are also identified at this stage.

- Step 4: Identify implementation architecture context for product at each life cycle process scenario and for organization at each life cycle process scenario within the scope of the development effort. Physical connections between the system and the environment elements define the physical external interface requirements. Physical parts are identified. Physical internal interfaces are defined by architecture connections and architecture flows among those parts. Allocation matrix relates physical parts and physical interfaces to the functions and functional flows.

4. The mobile TT&C ground station system concurrent engineering

This section presents the results obtained in the case study. It illustrates the steps listed in Section 3 highlighting where the proposed approach is different from traditional approaches. The proposed approach is stakeholder driven whereas traditional approaches are customer or user driven. In the various steps listed in Section 3, analyses are performed for each life cycle process scenario, simultaneously, for product and organization. Traditional approaches focus on product operation and development organization.

Figure 4 presents the life cycle processes and scenarios of a mobile TT&C ground station. The stakeholder, requirements, functional and implementation architecture analysis will be exemplified for the *Development, Installation, Operation and Maintenance* processes. In practice, steps 1 to 4 in Section 3 must be run for all life cycle process scenarios. The *Development* and *Maintenance* processes, in orange, are used to exemplify the *organization* life cycle process scenarios. And the *Operation* and *Installation* processes, in blue, are used to exemplify the *product* life cycle process scenarios. The Figures 5 to 16 just exemplify the steps for these selected processes.

Figures 5 and 6 exemplify the identification of *organization* stakeholders for *Development* and *Maintenance* life cycle process scenarios. This innovates the traditional focus on systems engineering the product. This approach recognizes that the system solution is not only made of *product* elements but also of *organization* elements. These Figures also capture the stakeholder concerns represented by the connections between the stakeholders and the central bubble, containing life cycle scenario.

Figures 7 and 8 present the *product* stakeholders identified and their concerns about *TT&C Station in Operation* and *in Installation* life cycle process scenarios. From stakeholders concerns, stakeholder requirements are identified and measures of effectiveness (MoEs) are derived. From stakeholder requirements, functions, performance and conditions are identified. Requirement analysis transforms stakeholder requirements into system requirements. System requirements will be met no only by product elements but also by organization elements.

Figures 9 and 10 depict the organization functional context for two life cycle process scenarios: *Development* and *Maintenance*. The links between the central ellipse and the elements in the organization environment at that scenario are identified. These links show the flows of information, material and energy between the environment and the system.

Figures 11 and 12 depict the product during *TT&C Station in Operation* and *in Installation* in the central ellipse and the elements in the environment during those processes. Links between product and environment are energy, material and information flows.

Besides each element in the environment, some of its potential states are necessary to be identified. For

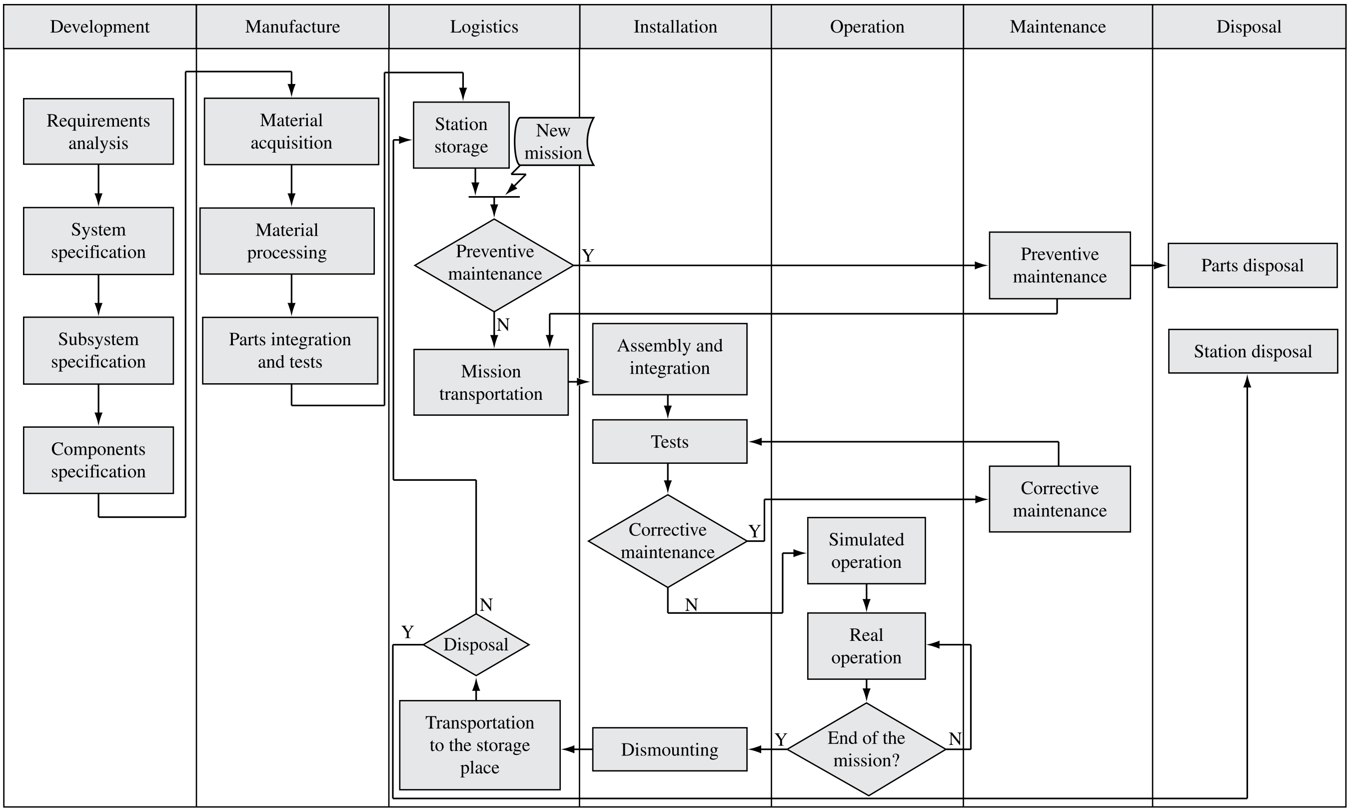

Figure 4. Life cycle process and scenarios.

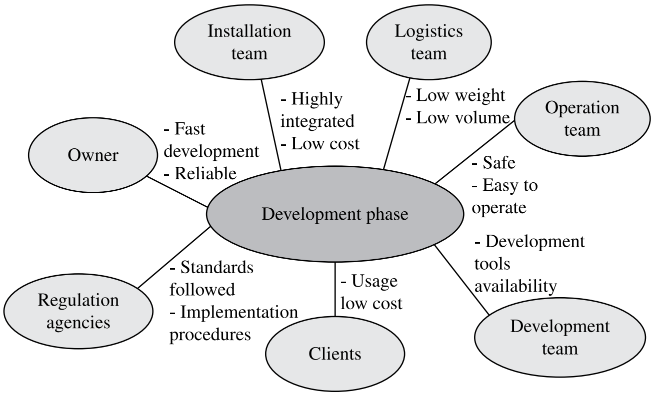

Figure 5. *Organization* stakeholders and their concerns for the *Development* phase analysis scenario.

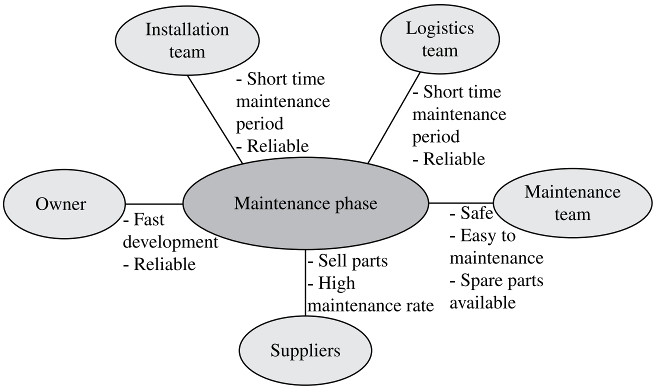

Figure 6. *Organization* stakeholders and their concerns for the *Maintenance* phase analysis scenario.

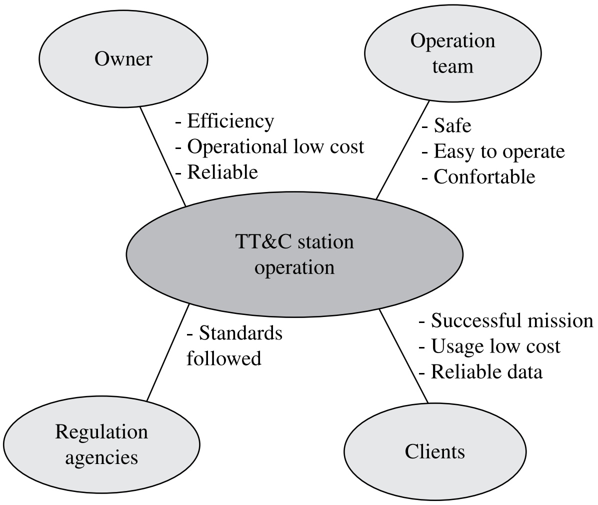

Figure 7. *Product* stakeholders and their concerns for the *TT&C Station in Operation* scenario.

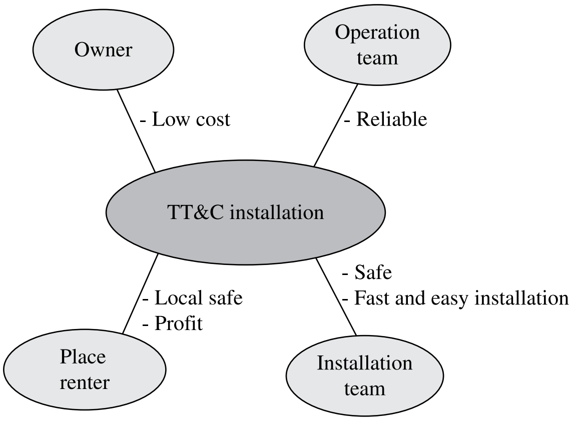

Figure 8. *Product* stakeholders and their concerns for the *TT&C Station in Installation* scenario.

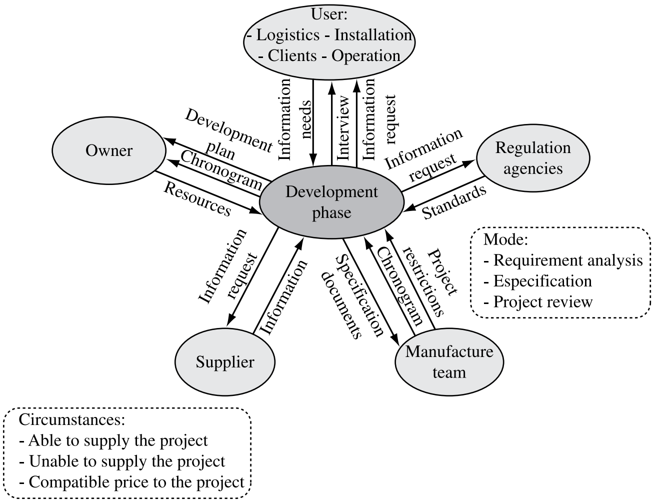

Figure 9. *Organization* functional context for the *Development phase* process scenario.

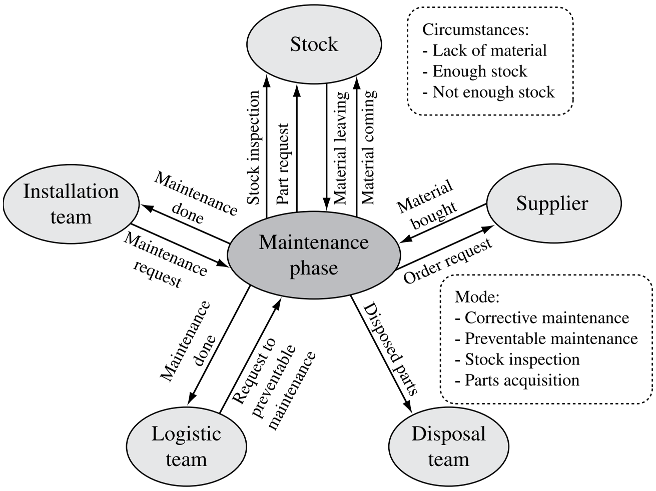

Figure 10. *Organization* functional context for the *Maintenance phase* process scenario.

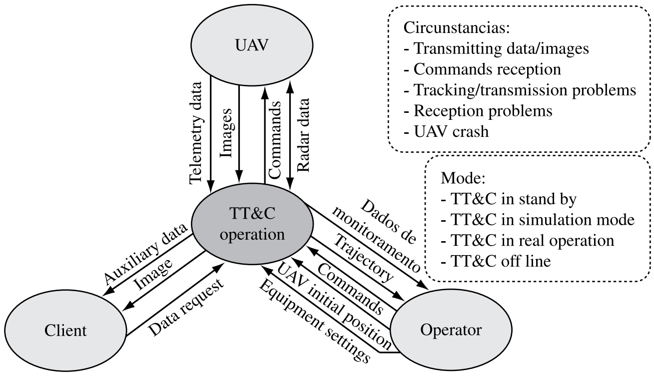

Figure 11. *Product* functional context for the *TT&C Station in Operation* process scenario.

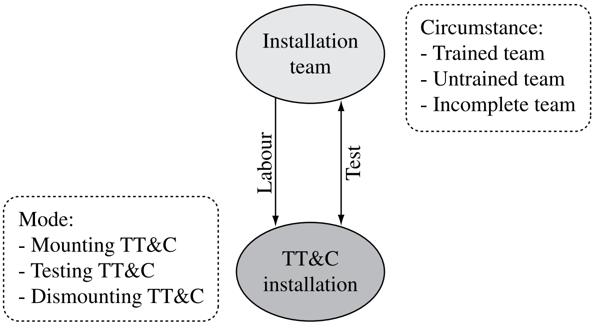

Figure 12. *Product* functional context for the *TT&C Station in Installation* process scenario.

illustration, Figures 9 and 11 present the potential states for one of their environment elements. Figure 9 shows the potential states for *Supplier* element which could be: i) it has condition to supply the project needs, ii) it has not condition to supply all the project needs, or iii) its price is compatible with project budget. Figure 11 shows the potential states for UAV element which could be: i) sending data/image, ii) receiving telecommands, iii) transmission/tracking/reception problems or iv) UAV broken. The composition with states of other elements in the environment results in the potential circumstances a system must cope with. The system must have different modes depending on the circumstances. Behavior modeling is required to show, under which conditions, system mode and system state transition occurs. Functions are identified per mode. Functions are identified from outside in by identifying which responses the system is supposed to give to deal with each stimulus provided by the environment elements. For each function, performance requirements are identified. Circumstances, flows between the system and the environment and function failures are sources of hazards. Risk analysis is performed on each identified potential hazard and exception handling functions are also identified at this stage.

Figure 13 presents the external physical connections between the *Development* organization and the elements in its environment. Figure 14 shows the *organization* physical architecture of the *Development* process with its internal

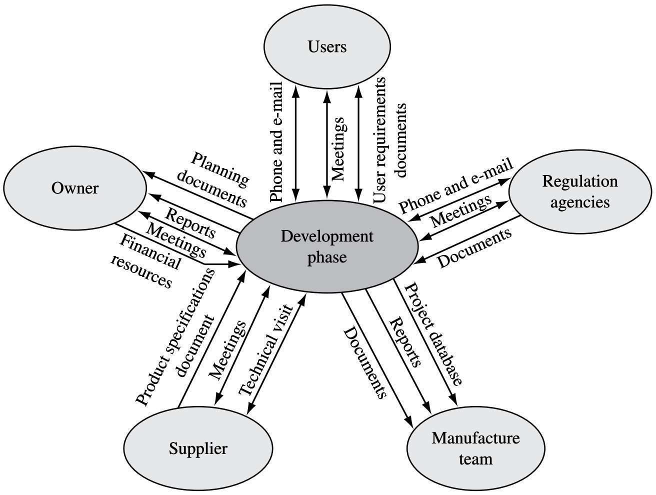

Figure 13. *Organization* implementation architecture context during Development process and external physical interfaces identified.

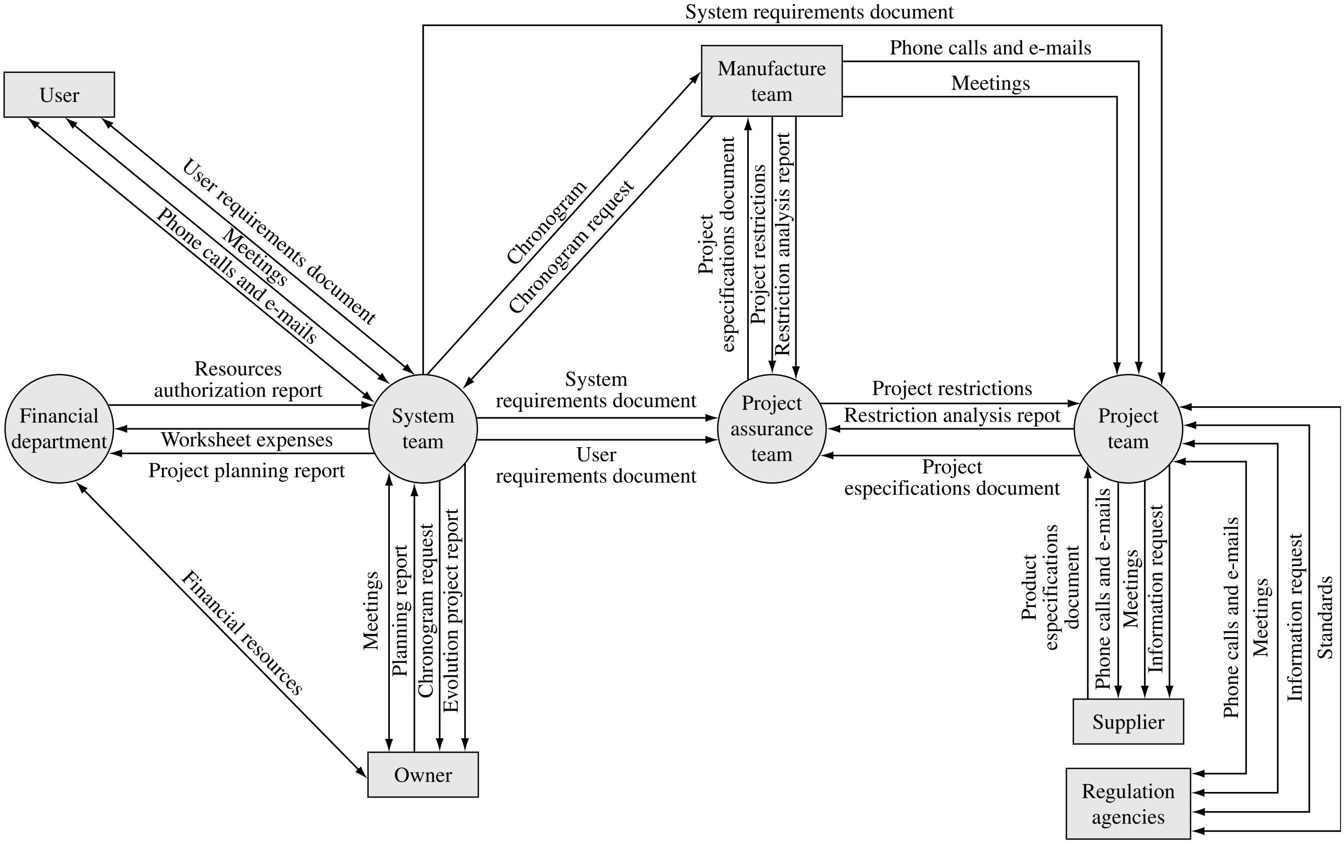

Figure 14. *Organization* physical architecture of *Development* process.

elements, the internal and external physical interfaces of each internal element. The rectangles represent the environment elements and the ellipses represent the internal elements.

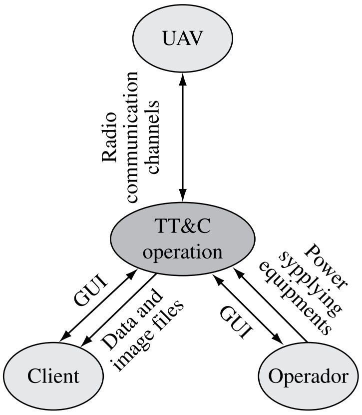

Figure 15. *Product* implementation architecture context during *Operation* process and external physical interfaces identified.

Figure 15 shows the *product* Mobile TT&C station and its external physical interfaces with the environment elements during the TT&C station in operation process. Figure 16 shows the decomposition of the *product* into its constituent parts and its internal and external physical interfaces. The rectangles represent the environment elements and the ellipses represent the internal elements.

5. Discussion

This section highlights the differences between traditional and proposed approaches.

Complex products such as the mobile TT&C ground station analyzed in this paper have many stakeholders. It is not possible to consider only customer or user as stakeholders of interests, like in the traditional approaches. Stakeholders related to all product life cycle process must be taken into consideration from the outset of the system architecting process. The proposed approach accomplishes it. (see Steps 1 and 2 in Section 3).

Traditional systems engineering approaches perform functional context analysis only during product operations (the so called CONOPS or concept of operations) and for

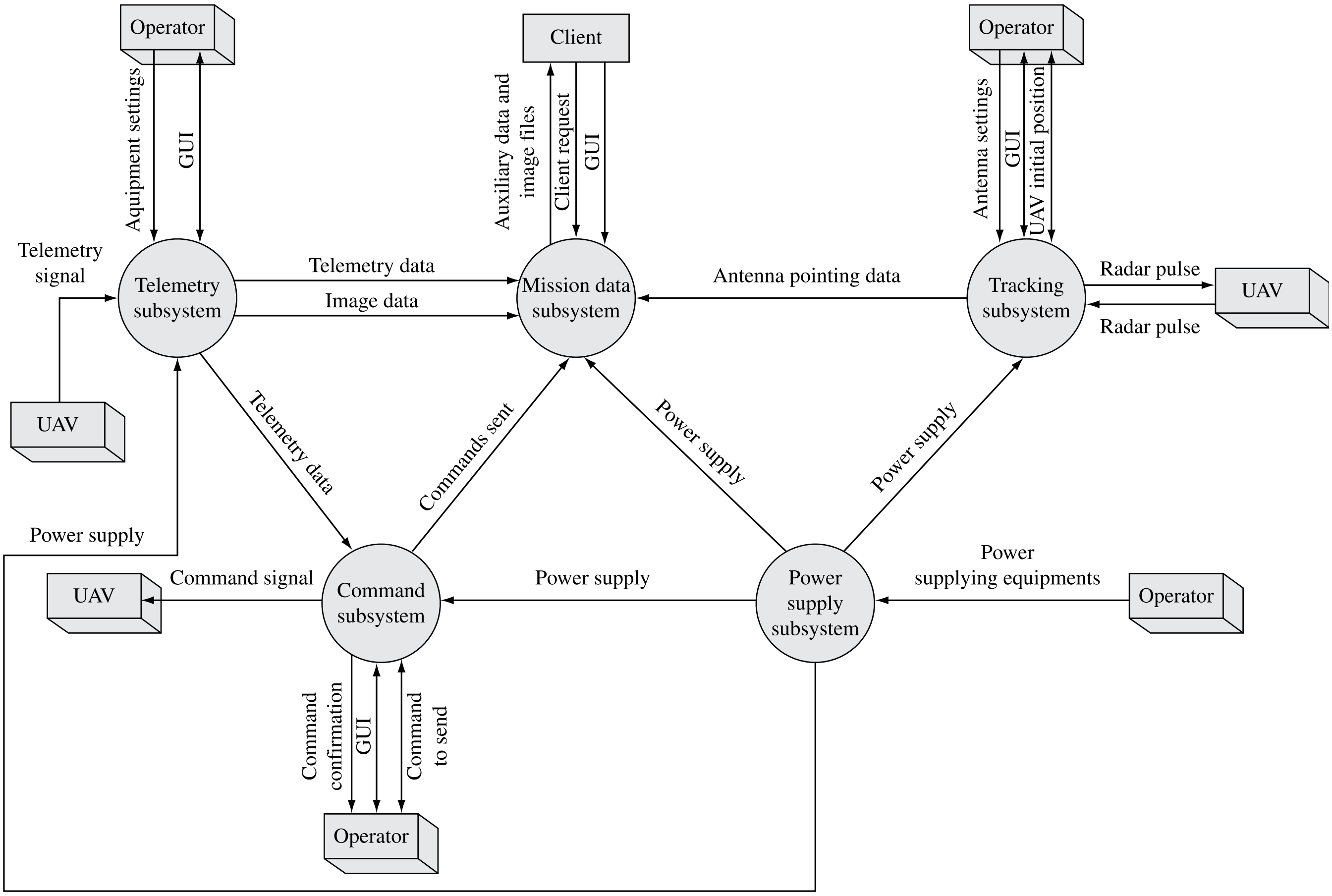

Figure 16. *Product* physical architecture of *Operation* process.

product development organization processes. However, a system solution is comprised of product and organization elements and many enabling elements must be also developed for mission success. These elements are only identified if context for each life cycle process scenario is performed. Therefore, the proposed approach covers the overall product life cycle, not only operations and development. (see Step 3 in Section 3).

By considering product life cycle processes from the beginning of the system architecting process and from the top level context diagrams to be decomposed in lower level functions and lower level physical architectures, the concurrent engineering concept is implemented within the systems engineering process. This fulfills the framework proposed in Figure 1.

The proposed approach allows requirements from the whole product life cycle to be anticipated to the early stages of a system architecting process. Stakeholder requirements are captured for the whole product life cycle process. Functions, performance, conditions, circumstances, modes and exception functions are captured for the whole product life cycle process. External physical and logical interfaces and internal physical and logical interfaces are identified for the whole product life cycle process.

The system solution here is composed of product and organization elements. The product interaction with other system elements is identified in the beginning of the system architecting process. This promotes dramatic gains in productivity during product development and during product life cycle. System quality increases. Product changes are avoided. Changes cost and time are eliminated.

6. Conclusion

This paper presented a system concurrent engineering approach to develop a mobile TT&C ground station. The proposed approach addressed the deficiencies of traditional methods, such as, product focus, operation and development focus, and part focus. The paper described the approach as a way to perform stakeholder analysis, requirements analysis, functional analysis and implementation architecture, simultaneously, for the product and organization elements of a system at every layer of the system breakdown structure. This is necessary to address all complexity factors that are inherent to complex product development. Conclusions are that impact, traceability and hierarchy links promote the anticipation of life cycle process requirements to the early stages of systems architecting. Late changes are avoided, development costs are dramatically reduced while satisfaction of stakeholders over product life cycle is increased.

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