System concurrent engineering for the development of an aeronautical navigation system

Geilson Loureiro, Alessandro Gonçalves Adinolfi, Carlos Eduardo Viana Ribeiro, Ricardo Castelo Branco de Andrade
National Institute for Space Research
e-mails: geilson@lit.inpe.br; alessandro.adinolfi@anac.gov.br; carlos.ribeiro2@honeywell.com; rcbandrade@ieee.org

Abstract: This paper presents a system concurrent engineering approach for the development of an aeronautical navigation system. Traditional approaches focus on the product, the development organization and the product's 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 organization are not taken into consideration. The system concurrent engineering performs stakeholder analysis, requirements analysis, functional analysis and implementation architecture analysis, simultaneously, for the product, its life cycle processes and their performing organization. From the analysis, requirements and attributes are captured for the product and its life cycle processes organization and the relationship between them is identified. We have concluded 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. In this paper the advantages of the concurrent engineering approach are evidenced along the development activities of an Aeronautical Navigation System.

Keywords: system concurrent engineering, aeronautical navigation system, systems engineering, concurrent engineering, complex product, integrated product development.

1. Introduction

This paper presents a systems concurrent engineering approach to develop an Aeronautical Navigation System. Such development activity has been made to show in an ordered, integrated and practical manner, the concept of systems concurrent engineering and its advantages.

The paper is organized as following: Section 2 presents the traditional systems engineering versus concurrent engineering approaches. Section 3 presents the systems concurrent engineering approach framework and method. Section 4 presents the models derived for the Aeronautical Navigation System using the approach. Section 5 discusses the advantages and opportunities for improving the proposed approach. Section 6 concludes this paper.

2. Traditional system engineering versus concurrent engineering

Aerospace products are complex. They are multidisciplinary products, they must cope with extreme environmental conditions over their life cycle (vibration, temperature, humidity, moisture, HIRF and others), they must undergo very strict assembly, integration and testing (AIT) procedures. AIT organizations are worth the order of hundred million dollars. There are many opportunities to improve productivity over aeronautical products life cycle if a concurrent engineering approach takes place from the beginning of the aeronautical products 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 [2,3,6,8]. 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 the 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 aerospace 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 of deploying

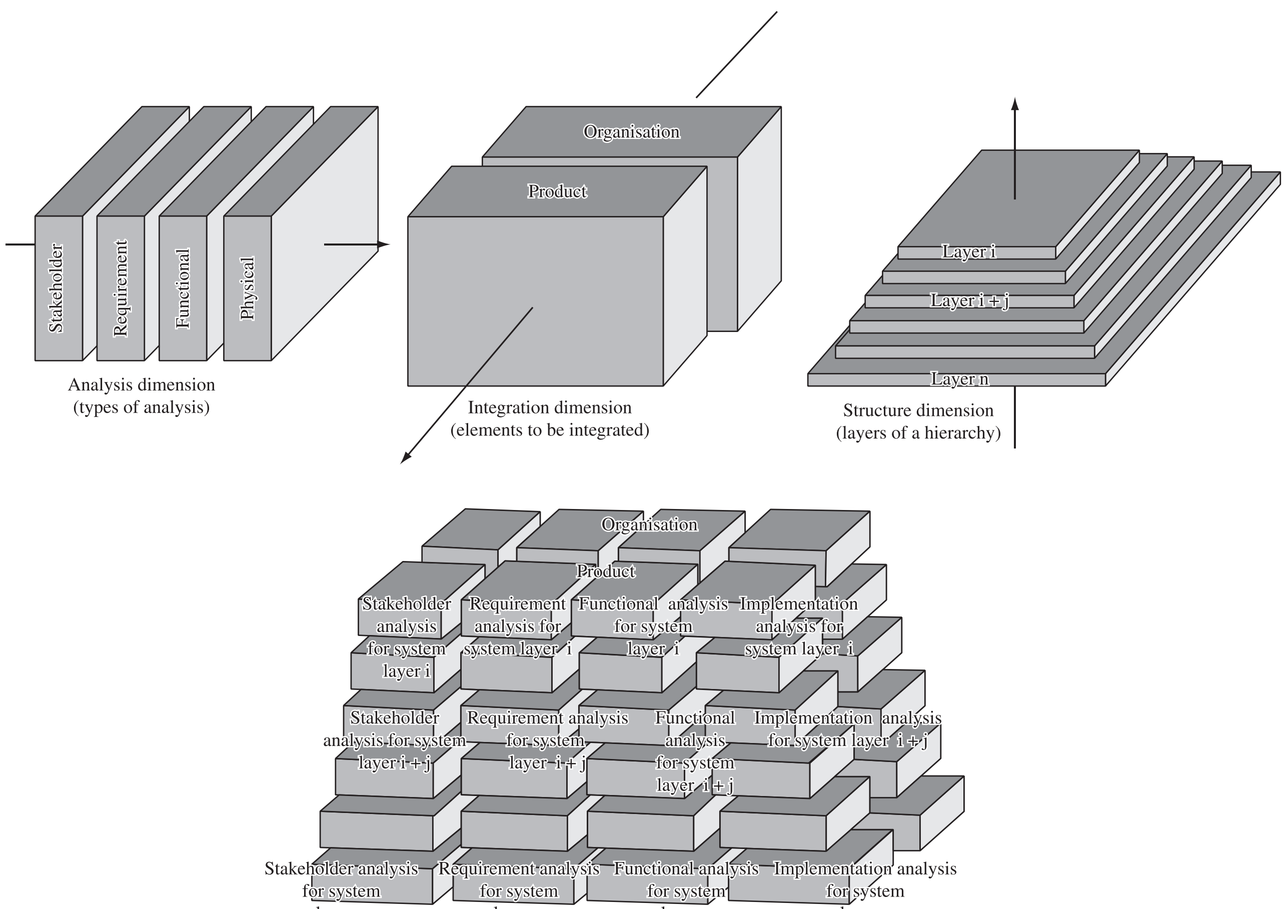

Figure 1. A framework to address complexity in complex product development – the total view framework.

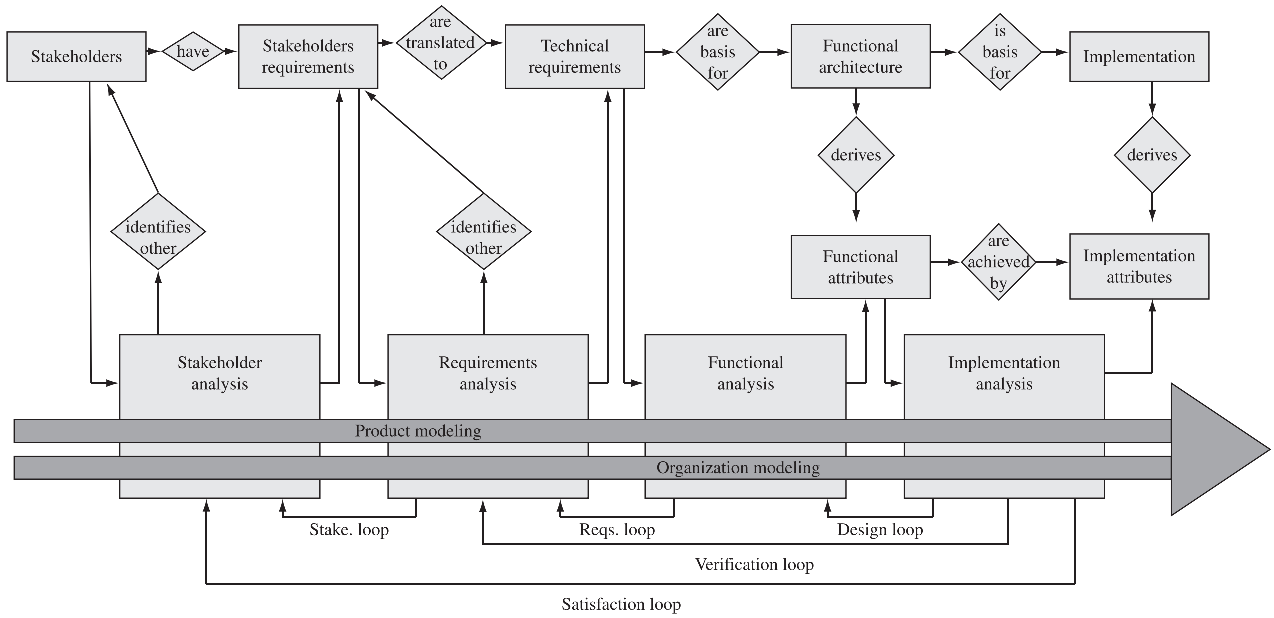

Figure 2. A method within the total view framework – the concurrent structured analysis method.

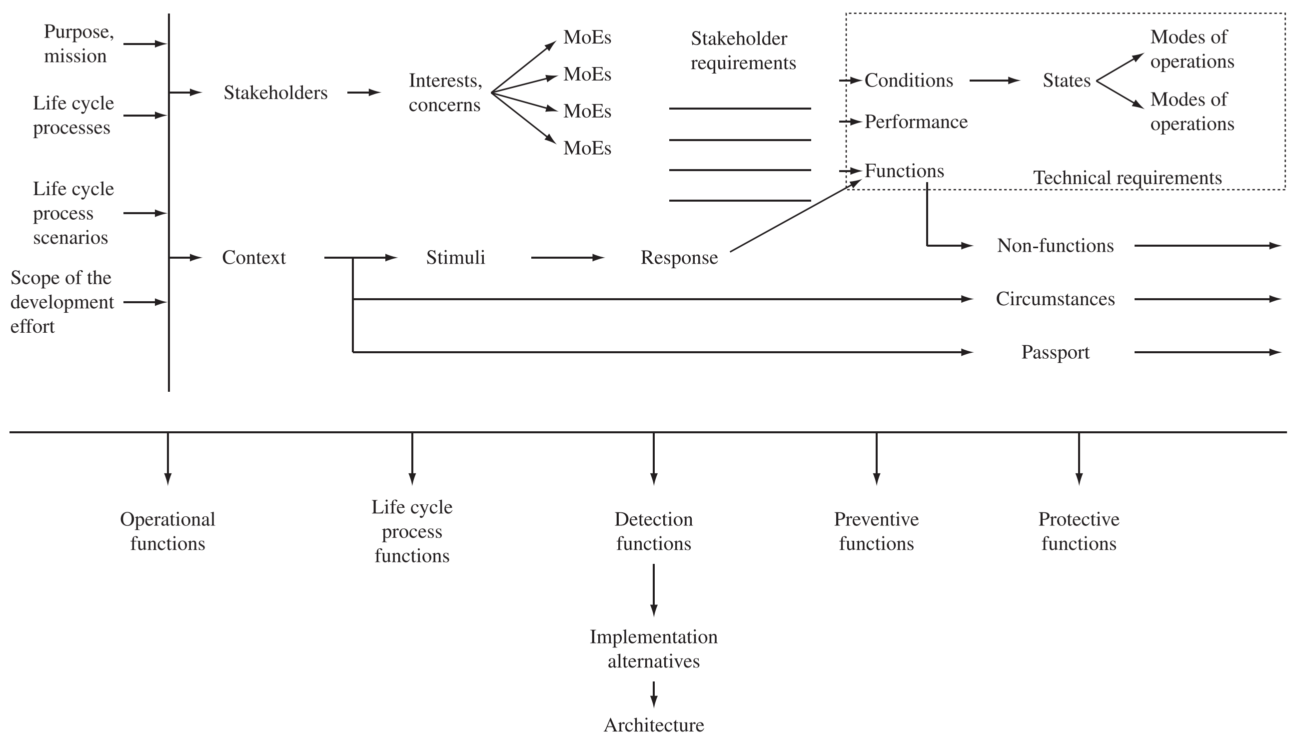

Figure 3. The system concurrent engineering method in detail.

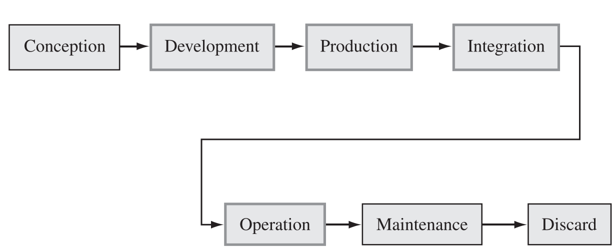

Figure 4. Life cycle processes.

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

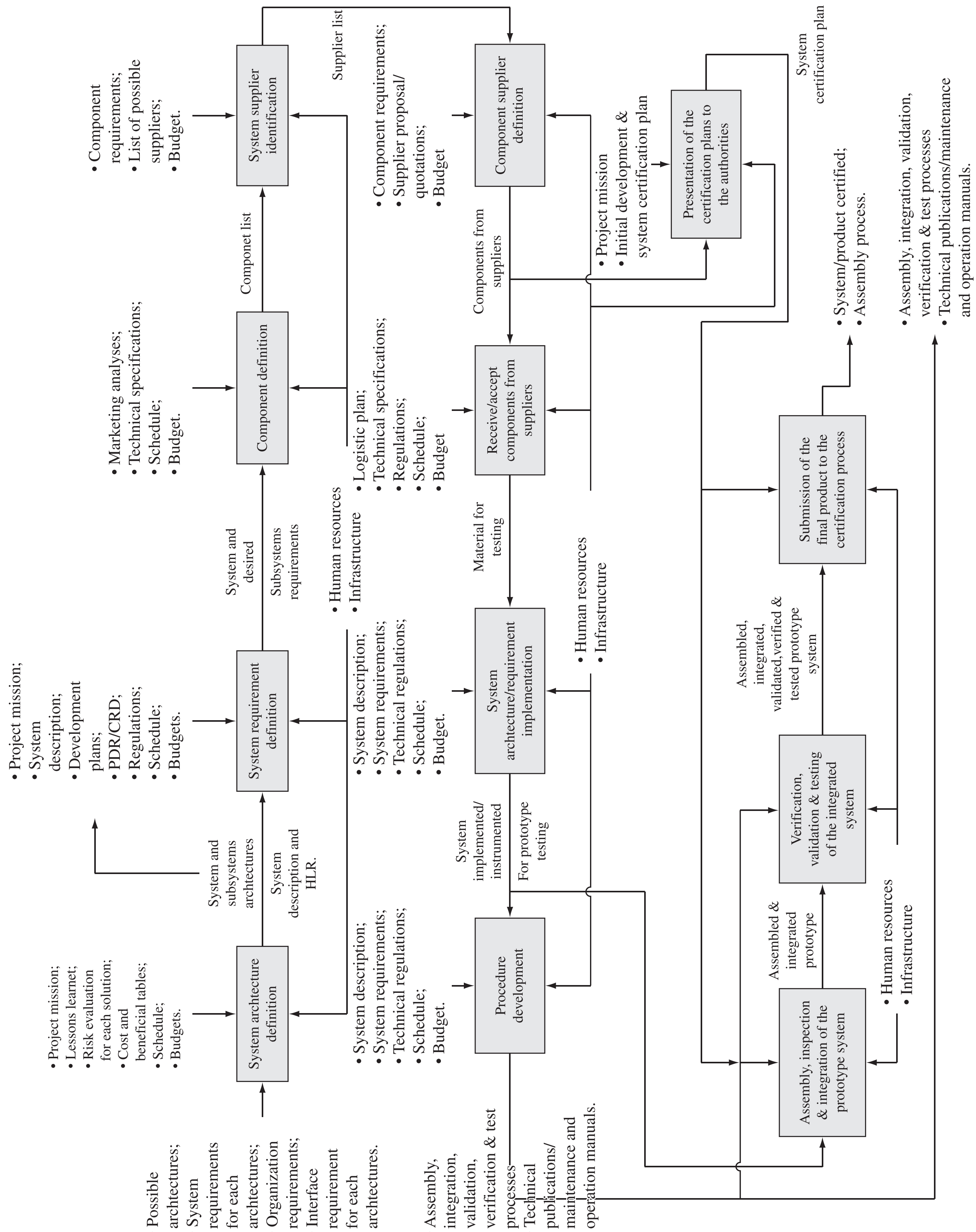

Figure 5. Life cycle scenarios of the Product Development process.

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 a hierarchy. System breakdown structures are also represented in hierarchies.

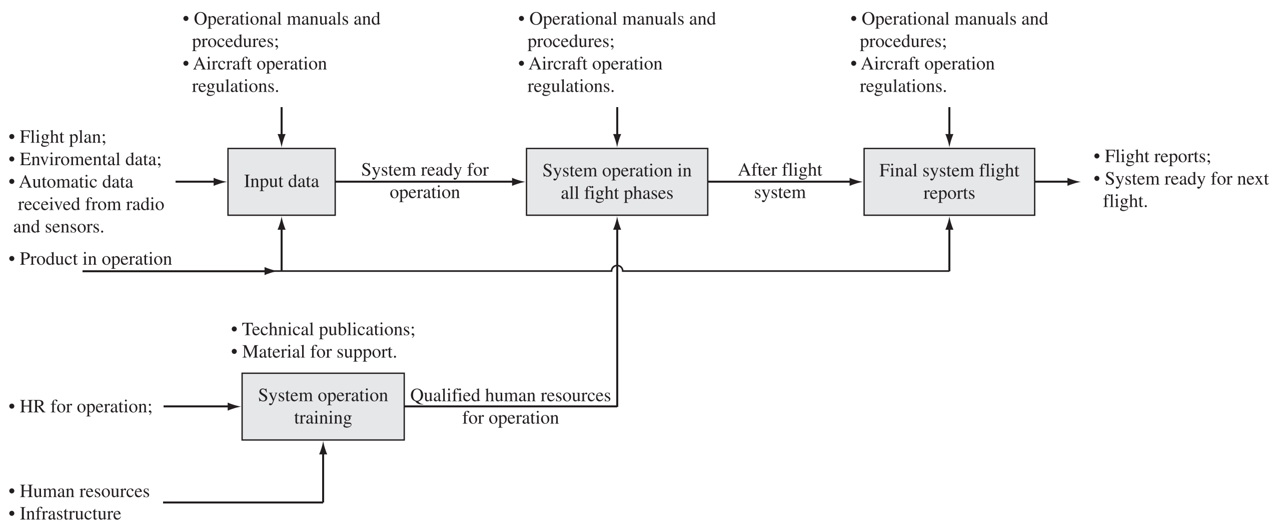

Figure 6. Life cycle scenarios of the Product Operation process.

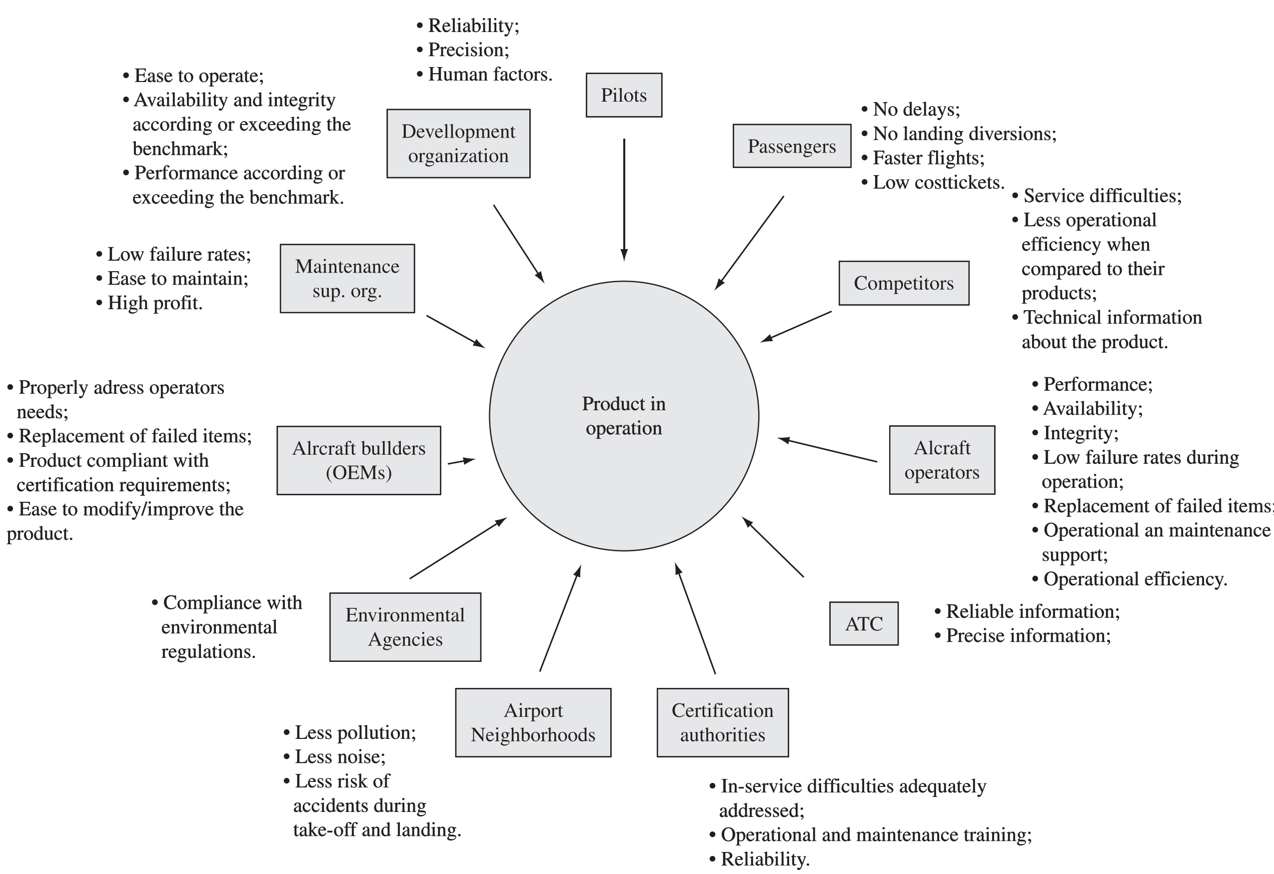

Figure 7. Product stakeholders and their concerns for the “Product in Operation” analysis scenario.

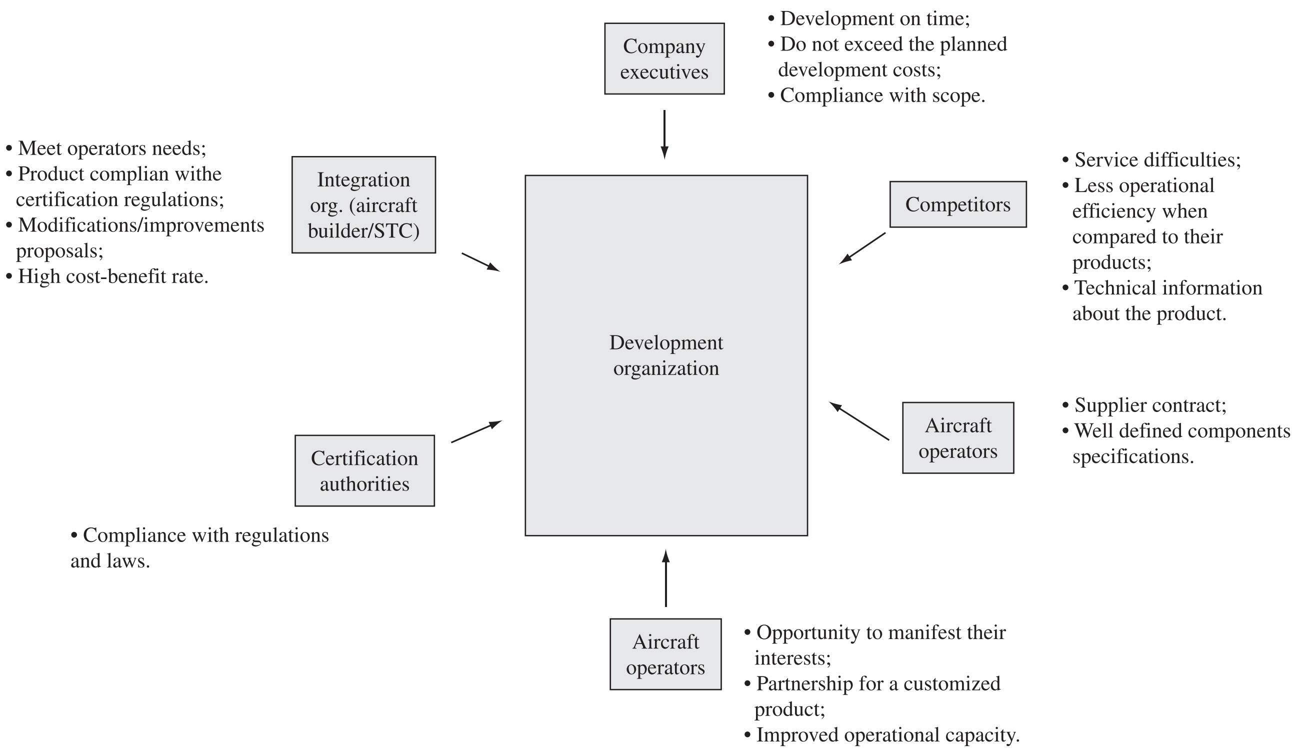

Figure 8. Organization stakeholders and their concerns for the “Development Organization” analysis scenario.

Table 1. Examples of MoEs.

Scenarios	Stakeholders	Interests	How to measure compliance to interest?
Product in Operation	Airliners	Low failure rates in operation	To monitor how many removals were done due to component failures (MTBUR vs MTBF).
Product in Integration	Certification Authorities	System integrated into the aircraft complies with requirements	To verify if integrated product (product and manual of integration instructions) complies with Part 23, Subpart F.
Organization in Development	Upper Management	Development cost bellow budget	To monitor development costs.
Organization in Production	Selling Organization	Demand compliance	To monitor production rates.

Table 2. Examples of requirements.

Scenario	Requirement	Type	Compl	Const	Comments
Product in Operation	Product MTBF shall be at least TBD hours.	P	M	Y	Mandatory since those assumptions are used for certification.
Product in Integration	Product shall comply with Part 23	F	M	Y	
	Integration and operational manuals shall comply with Part 23	P/C	M	Y	
Development Organization	Development organization shall elaborate development cost forecast for each scenario.	F	M	Y	It is mandatory development organization to foresee costs considering budgets for each phase. Margins are negociable.
	Development cost for each scenario shall not exceed US$ TBD.	P	D	N	
Production Organization	Production organization shall have installations in order to product TBD units per month.	F	M	Y	It is hard to react rapidly react to a demand without adequate installations.
	Production organization shall have human resources in order to product TBD units per month.	F	D	N	Demand increase may lead to extra time or shifts.

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

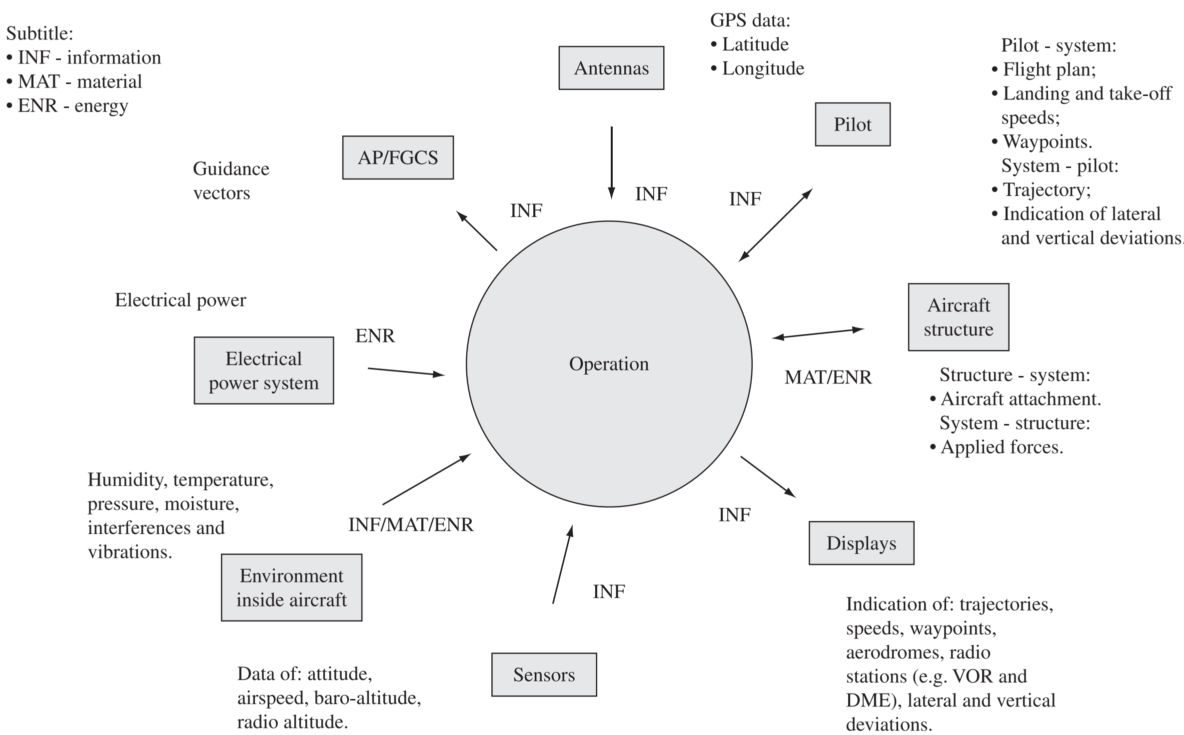

Figure 9. Product functional context for "Product in Operation" process scenario.

Table 3. "Product in Operation": Examples of modes and circumstances.

Circumstances		System Mode
Antennas	Operational	Operational
	Partially failed (at least one valid source)	Operation with no redundancy
	Failed	Failed
Airplane internal environment	Favorable or inside operation specifications	Operational
	Unfavorable or outside operation specifications	Failed
Displays	On/Operational	Operational
	On/Failed	Failed
	Off	Standby
Pilots	Manually or automatically navigation: without errors	Operational or Failed
	Manually or automatically navigation: with errors	
Structure	In accordance with detailed design	Operational
	Outside specifications	Failed
Sensors	On/Operational	Operational
	On/Partially failed (at least one valid source)	Operational
	On/Failed	Failed
	Off	Failed
Electrical System	Operational (25 - 32V)	Operational
	Operational (1 - 24V or 32V+)	Failed
	Failed (short)	Failed
	Off	Off

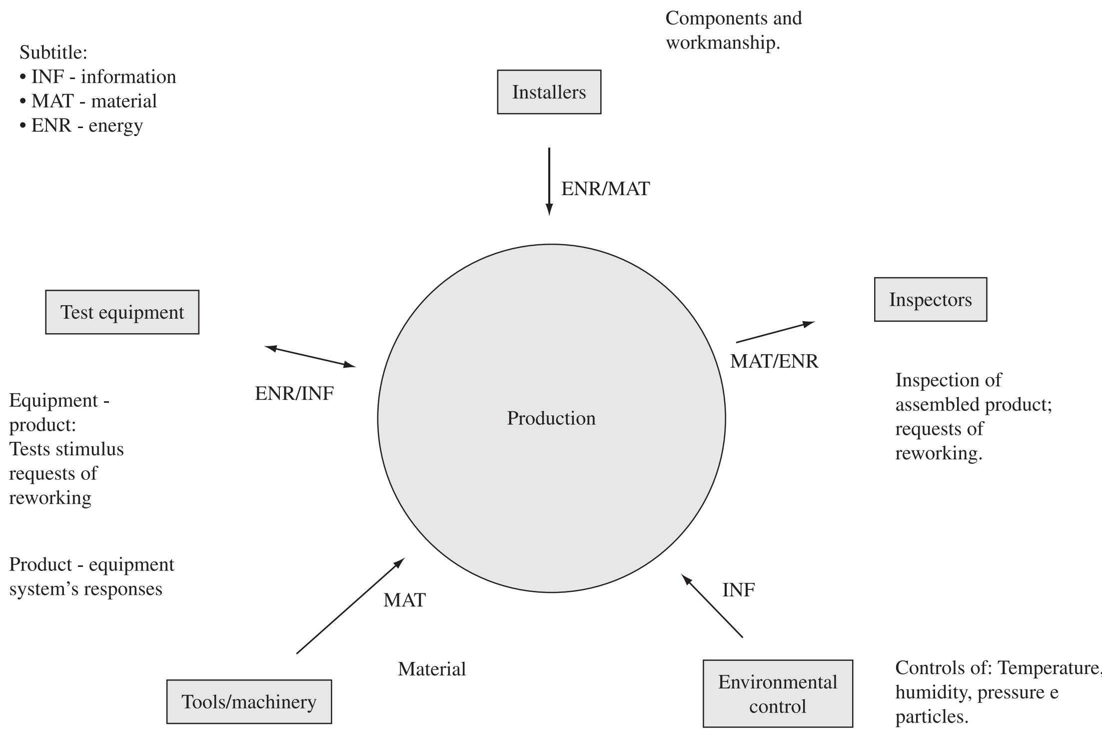

Figure 10. Product functional context for "Product in Production" process scenario.

Table 4. "Product in Production": Examples of modes and circumstances.

Circumstances		Modes
Installers	Manfunction	System with defects
	Loss of function	System not available
Inspection	Manfunction	System with defects
	Loss of function	System with defects
		System not available
		System without defects
Environmental control	Manfunction	System with defects
	Loss of function	System not available
		System with defects
Tooling	Manfunction	System with defects
	Loss of function	System not available
Test team	Manfunction	System with defects
	Loss of function	System with defects
		System not available
		System without defects

are performed at the car layer, at the powertrain 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:

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. 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

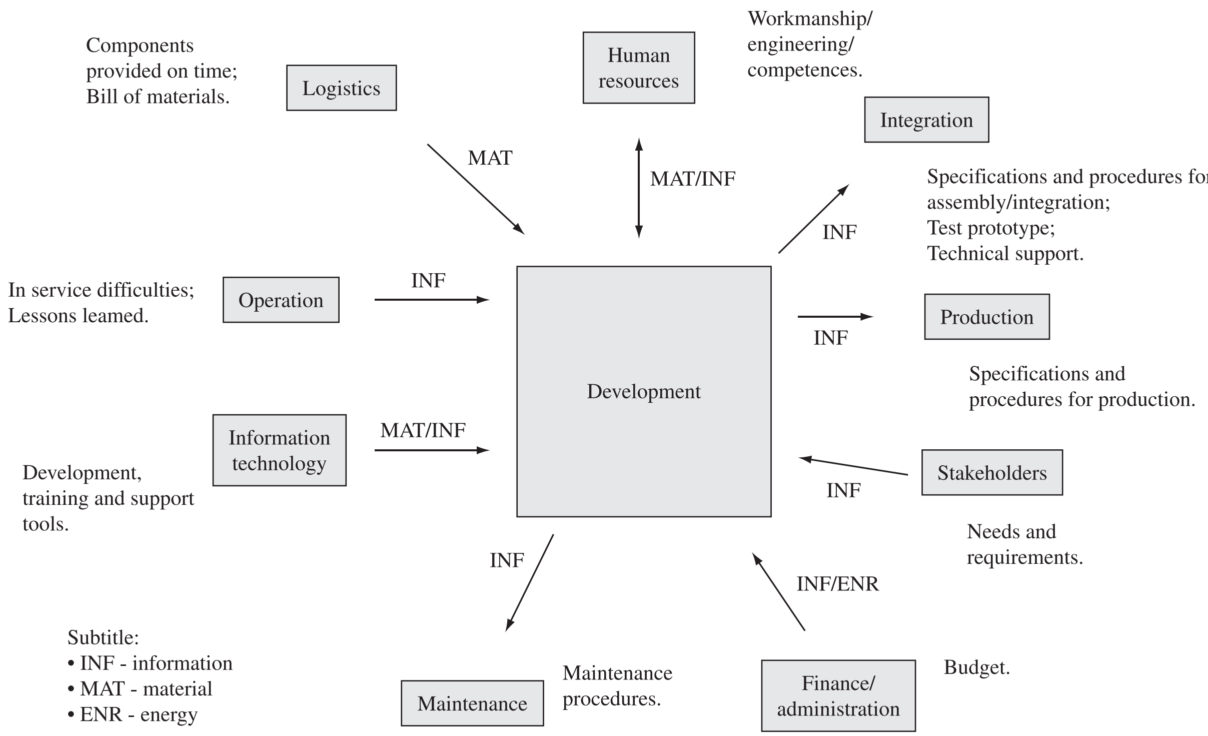

Figure 11. Organization functional context for "Development Organization" process scenario.

Table 5. "Development Organization": Examples of modes and circumstances.

Circumstances		**Modes**
Human Resoureces Finances	Malfunction	Unbalanced organization (Do not have all or some needed competences)
		Unmotivated organization (Do have the needed competences but without correct focus or needed resources)
		Inexistent organization (Do not product what is needed or erroneously product it)
	Loss of function	Unbalanced organization
		Unmotivated organization
		Inexistent organization
Airplane Integration Production Maintenance Operation	Malfunction	Unbalanced organization
		Unmotivated organization
		Inexistent organization
		- (It does not define a specific mode of the development organization)
	Loss of function	-
IT Logistics	Malfunction	Unmotivated organization
		Inexistent organization
	Loss of function	Unmotivated organization
		Inexistent organization

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

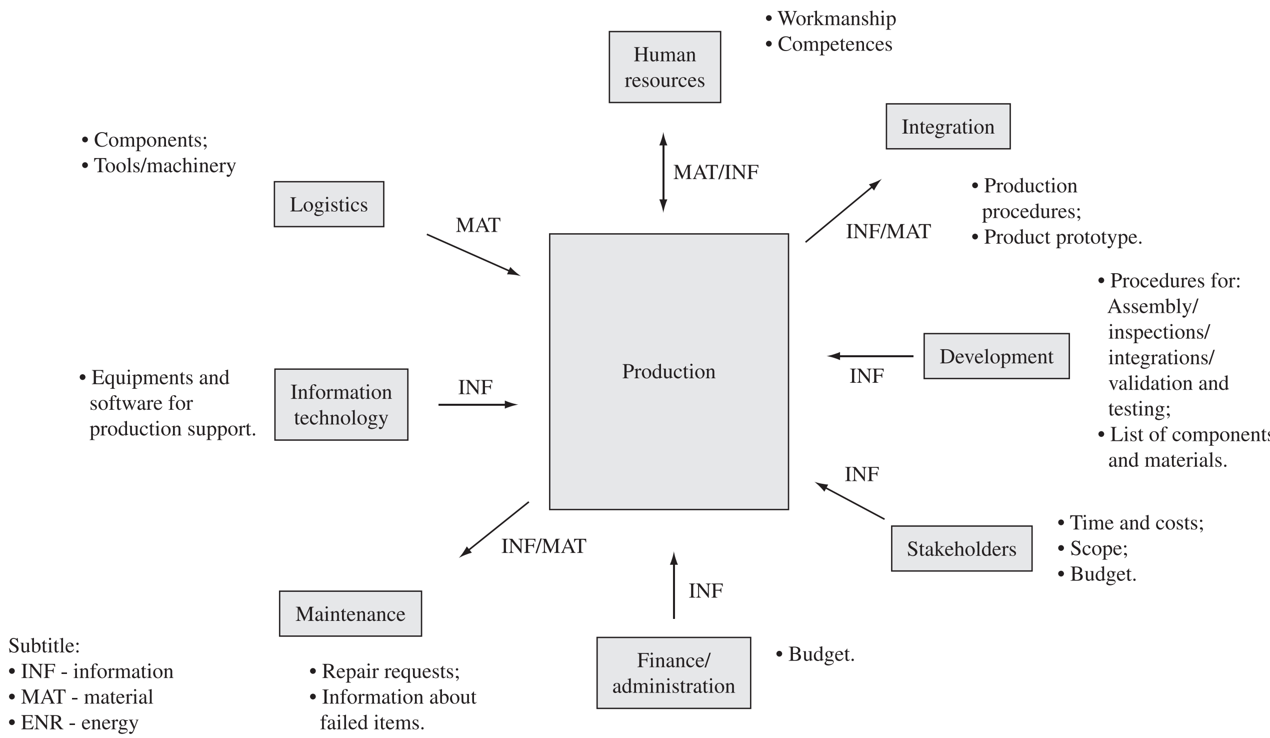

Figure 12. Organization functional context for “Assembly Organization” process scenario.

Table 6. “Assembly Organization”: Examples of modes and circumstances.

Circumstances		**Modes**
Airplane integration	Malfunction	Unbalanced organization (Do not have all or some needed competences)
		Unmotivated organization (Do have the needed competences but without correct focus or needed resources)
		Inexistent organization (Do not product what is needed or erroneously product it)
	Loss of function	-
		(It does not define a specific mode of the development organization)
Development logistics	Malfunction	Unmotivated organization
		Inexistent organization
	Loss of function	Unmotivated organization
		Inexistent organization
Human resources finances	Malfunction	Unbalanced organization
		Unmotivated organization
		Inexistent organization
	Loss of function	Unbalanced organization
		Unmotivated organization
		Inexistent organization

Table 7. “Product in Operation”: Example of Hazards.

Origin	**Cause**	**Hazard**	**Failure**	**Consequence**	**Severity (1-5)**	**Probability (1-5)**	**Risk (SxP)**
CL	GPS signal misleading	Non-annunciated failure	Compution or deviation indication error	It may lead the pilot to erroneously navigate the airplane	5	1	5
PS	One channel power cable rupture	Loss of redundancy of navigation system	Loss of power of one channel	Loss of redundancy	1	2	2
NF	Deviation indication misleading	Non-annunciated failure	Compution or deviation indication error	It may lead the pilot to erroneously navigate the airplane	5	1	5

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. Behaviour modelling 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.

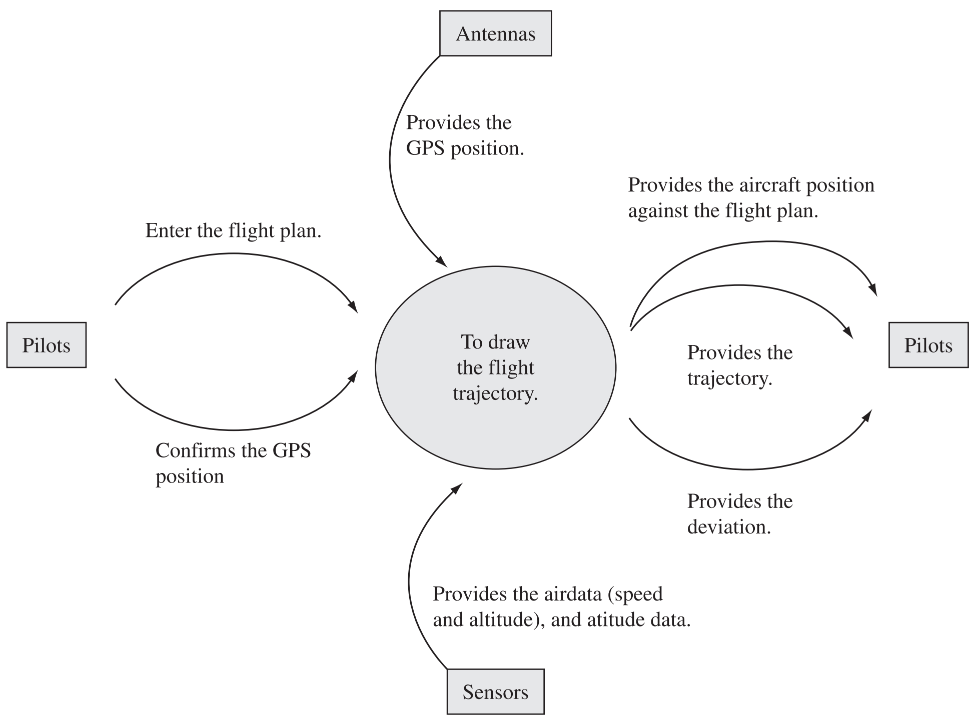

Figure 13. "Product in Operation": Context essential diagram.

Table 8. "Product in Operation": Events list.

System Stimulus	#	System Responses
Pilots insert the flight plan.	1	System receives the flight plan.
Antennas provide the airplane position (GPS).	2	System receives the airplane position.
Sensors provides the attitude, altitude and speed data.	3	System receives the attitude, altitude and speed data.
Pilots confirms the geographic airplane position.	5	System receives the confirmation of the airplane position.
Pilots receives the suggested airplane flight trajectory, including constrainsts of speed and altitude of defined for each waypoints.	4	System suggests the airplane flight trajectory, including constrainsts of speed and altitude of defined for each waypoints.
Pilots confirms the suggested airplane flight trajectory, being able to modify any waypoint or any altitude or speed constraints defined in the flight plan.	7	System displays the flight plan to be used during the flight, showing the starting point at the airplane current point.
Pilots receives the airplane deviations.	8	System calculates and displays the airplane deviations against the defined flight plan.
Pilots corrects the airplane position during flight.		System calculates and displays the new airplane deviations against the defined flight plan.

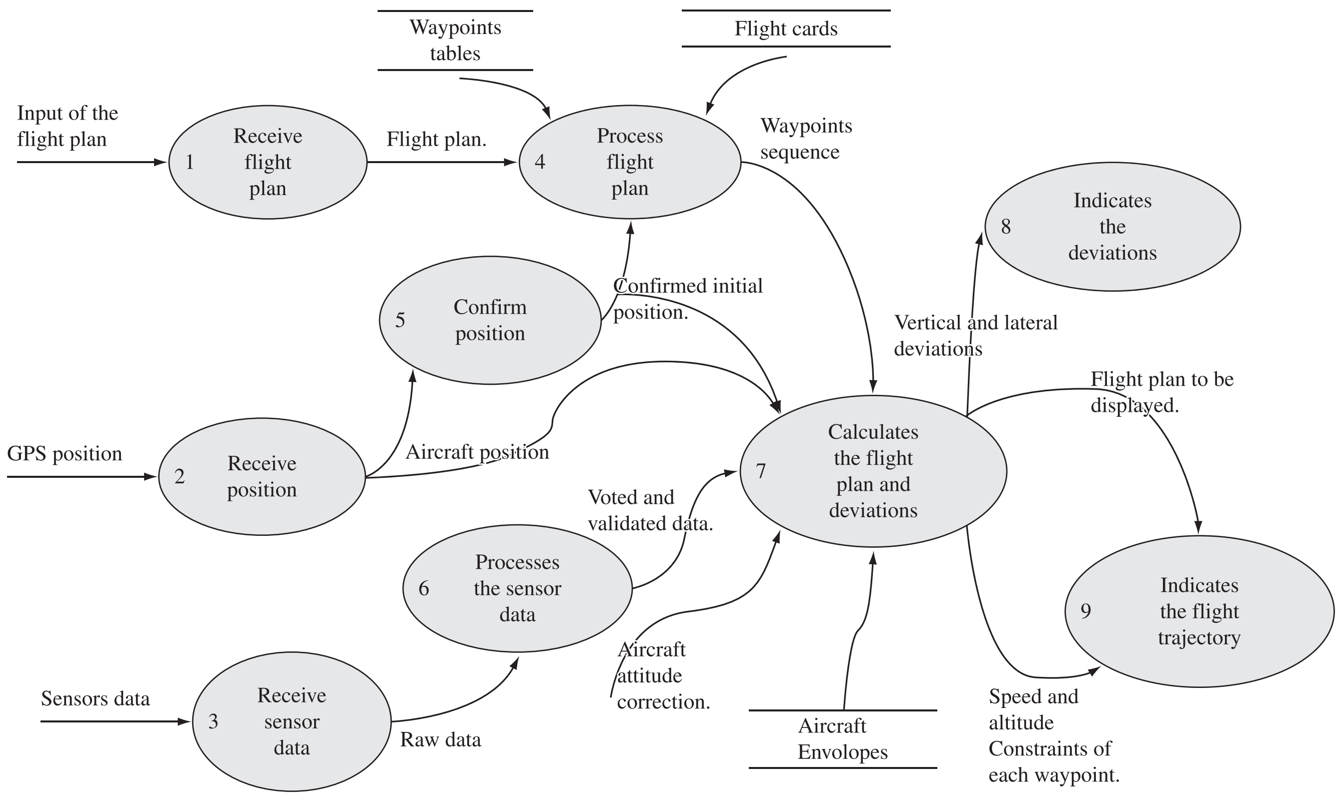

Figure 14. "Product in Operation": DFD diagram related to the Event List.

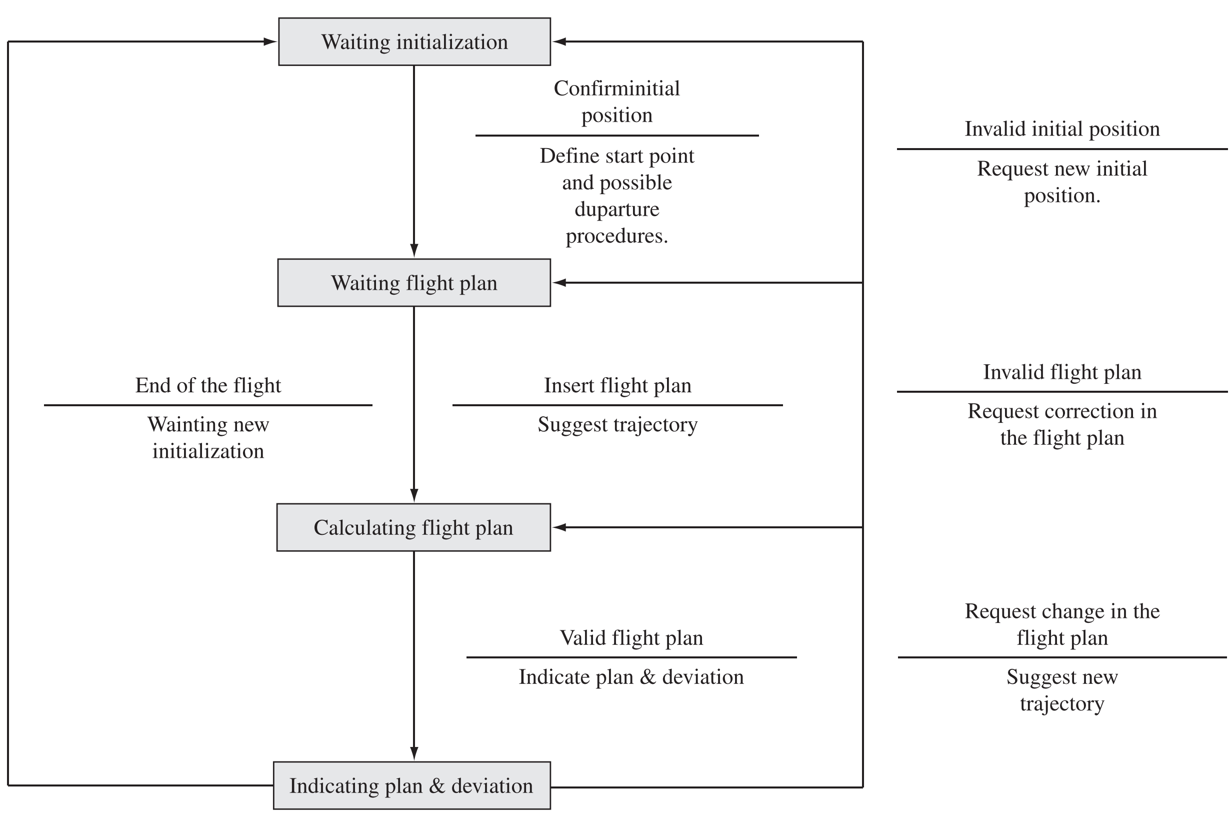

Figure 15. "Product in Operation": State Transition Diagram.

4. The Aeronautical Navigation System Concurrent Engineering

This section 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 users 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.

The first step is to define the system mission: It seems simple at first, but the clear statement of a mission will have an impact in the entire business, since it defines the focus for the entire integrated process. It defines what the

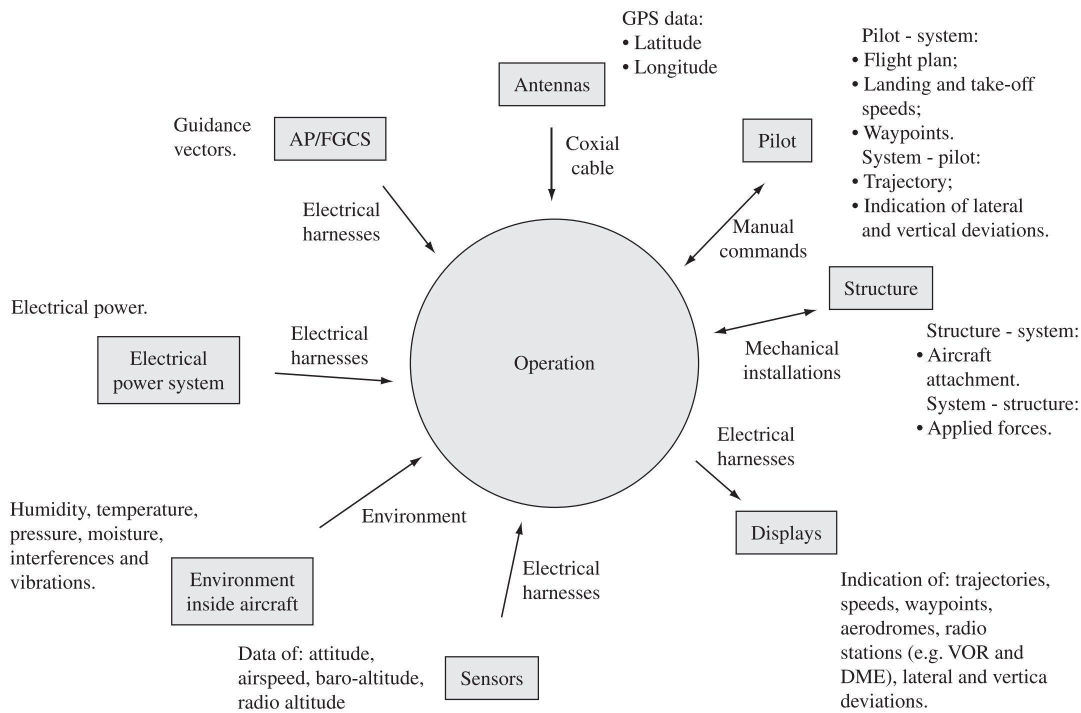

Figure 16. Product architectural context for "Product in Operation" process scenario.

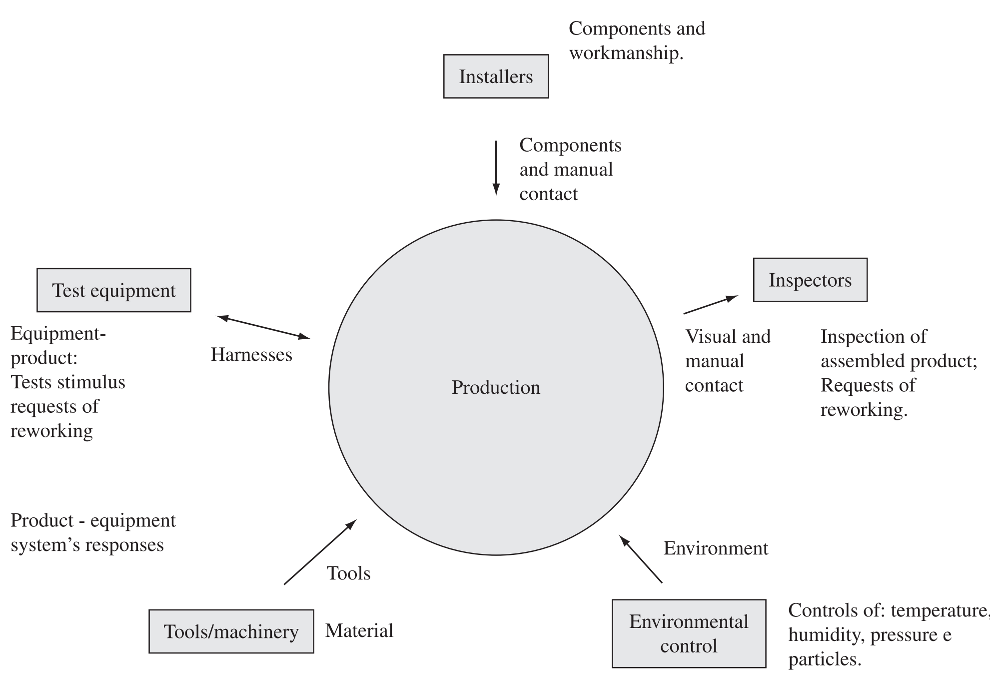

Figure 17. Product architectural context for "Product in Production" process scenario.

system intends to be and what does not. The Aeronautical Navigation System's mission was defined as: To provide automatically flight path vectors in order to comply with the flight plan for small aircraft.

Figure 4 presents the life cycle processes and scenarios of an Aeronautical Navigation System highlighting the processes to be executed by the development organization. Figure 5 and Figure 6 show in detail the steps of the life cycle processes, using IDEF0 diagrams. A good knowledge of the life cycle processes is important to correctly identify the implications for each process along the product's life, such as level of complexity, need of resources and stakeholders. These activities accomplish the Step 1, as explained in the Section 3 of this paper.

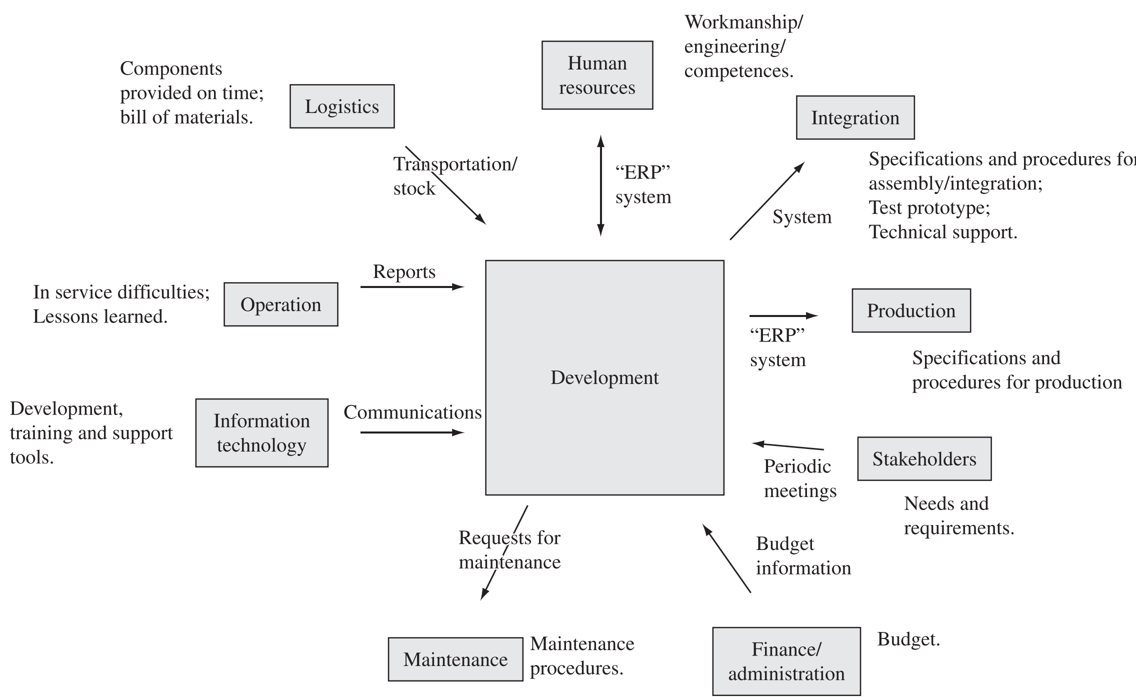

Figure 18. Product architectural context for "Development Organization" process scenario.

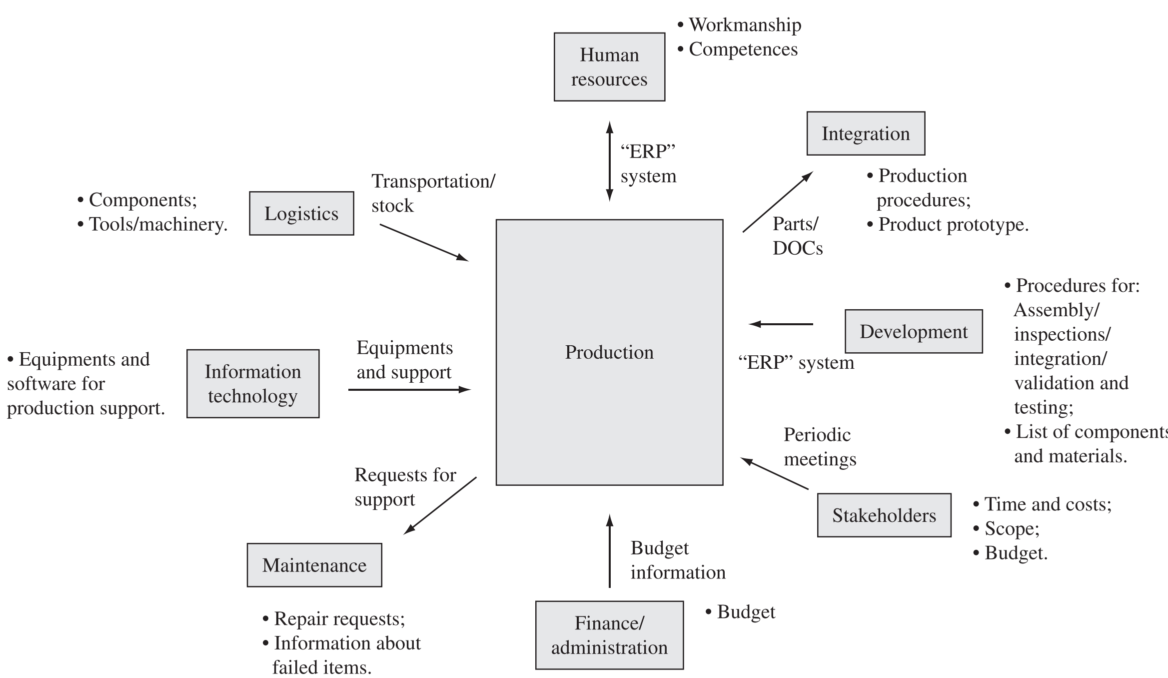

Figure 19. Product architectural context for "Assembly Organization" process scenario.

Figure 7 to Figure 8 and Table 1 to Table 2 exemplify the Step 2, as explained in the Section 3 of this paper, which means the activities from the identification of stakeholder and their interests until the determination of the High Level System Requirements.

Complex products such an Aeronautical Navigation System analyzed in this paper have many stakeholders. It is not possible to consider only customer or users as stakeholders of interesting, like in the traditional approaches, since there are more people or organizations that may have impact or influence during the system life cycle. Stakeholders related to all product life cycle process must be taken into consideration from the outset of the system architecting process. Figure 7 and Figure 8 exemplify the identification of stakeholders for the product during operation life cycle and for the organization during the product development life cycle.

Traditional systems engineering approaches perform functional context analysis only during product operations (the so called CONOPS or concept of operations) and for 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. Figure 9 to Figure 12 and Table 3 to Table 6 exemplifies the functional context, modes and circumstances, not only for the Product in Operation and Development Organization, as in the classical Systems Engineering approach, but also include examples for Product in Production and Assembly Organization. These activities are part of the Step 3 activities, as explained in the section 3 of this paper.

As part of the Step 3 there are also the identified hazards, as exemplified for Product operation in the Table 7.

Figure 13 to Figure 15 and Table 8 show the continuation of Step 3, which is still approaching the functional aspects of the system. In the figures it is exemplified the sub-scenario of Normal Operation of the System.

Figure 16 to Figure 19 are analogous to the previous Figure 9 to Figure 12, but they show the interfaces in architectural terms, which points not to problems (requirements), but to solutions (implementation). These activities are important part of step 4, as defined in the Section 3.

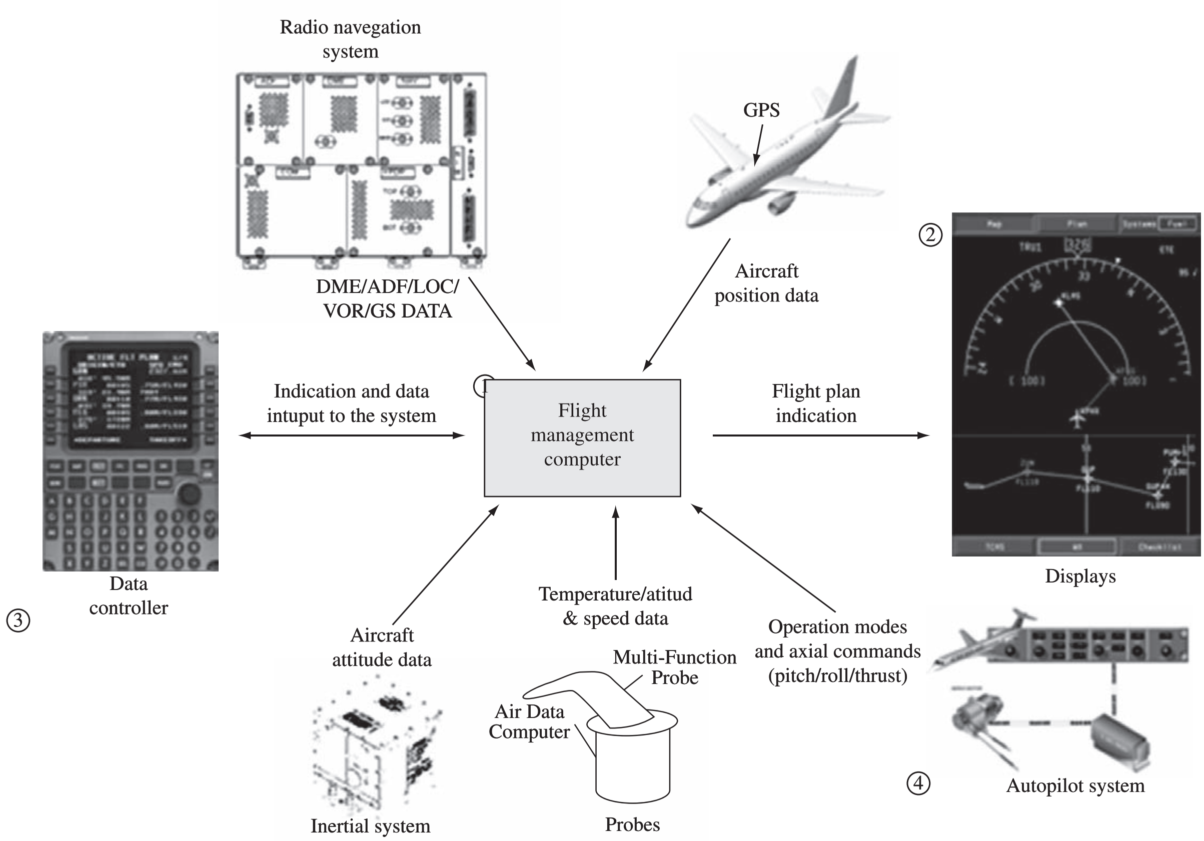

Figure 20. Interconnection Fluxes and Architectural Diagram of the Aeronautical Navigation System.

Table 9. Function and Parts of the Aeronautical Navigation System.

Action/Activated Processes	1	2	3	4
Enter the flight plan			x	
Navigation database	x			
Performance database	x			
Lateral commands	x			x
Vertical commands	x			x
Trajectory calculation	x			
Buffer for flight plan	x			
Flight data indication			x	
Trajectory indication		x		

Figure 20 and Table 9 show the final decisions in terms of architectural implementation, detailing the subsystems, components and function allocated for each subsystem.

5. Discussion

This section highlights the differences between traditional and proposed approaches.

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 fulfils 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. Therefore, costs and development time are reduced.

6. Conclusion

This paper presented a system concurrent engineering approach to develop an Aeronautical Navigation System. 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.

The Concurrent Systems Engineering proved to be an expensive and complex approach. Its benefits are proportional to the complexity of the system. There must be criteria to apply this approach, in order to avoid an unnecessary complex process for not complex systems. However, in the case of Aerospace Systems, which are increasingly complex systems, the benefits of this approach in terms of better definition of the product, organization optimization and reduction of latter changes largely exceed the costs of the Concurrent System Engineering approach.

7. Acknowledgements

The authors would like to thank INPE (the Brazilian National Institute for Space Research, www.inpe.br) for the post graduate course and the case study opportunity.

The authors would like to thank Honeywell do Brasil (www.honeywell.com), Embraer (www.embraer.com.br) and ANAC (Brazilian National Civil Aviation Agency, www.anac.gov.br), by the time received for investing in technical researches and personal development.

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