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# THE APPLICATION OF SYSTEMS ENGINEERING ON THE BUILDING DESIGN PROCESS

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## ABSTRACT
The evolution in the design process is usually based on the choice of a method for designing the system, in which its preference is previously selected by a process available to use and not by an open selection process. An open system approach is both a technical approach to design concepts and a preferred business strategy that is becoming widely applied by manufacturers of large complex systems. Although systems engineering consider both the business and the technical needs of customers, their goals is to provide a quality product that meets all user needs. This paper describes the capabilities of using some available systems engineering standards (like *EIA-632*) in the design process. Then, a methodological approach will be proposed for the practice of requirements engineering by applying quality assessment and control to design in early phases. This paper also discusses the need for a rigorous systems engineering process, which incorporates open systems concepts and principles to make a design method more or less appropriate by promoting multiple sources of supply and technology insertion. To demonstrate the applicability and efficiency of those standards, an application case study focusing more on applying systems engineering concepts to the building design is described along with verification and validation processes.

## INTRODUCTION
Systems engineering (SE) is an emergent discipline based on a structured approach towards the specification, design, acquisition, integration, reengineering, and implementation of a complex system over its life cycle. This emergent discipline has been applied mainly to scale complex systems and projects in the aeronautic (e.g. won et al. 2001), military (e.g. Hoang et al. 1996) and space (Shishko, 1995) industry since the late nineties; there is a great interest in applying such good practice in building design and practically manufacturing and production systems.
In the case of buildings, real design projects typically require the systems-level cooperation of experts from several engineering disciplines. Nowadays systems-level considerations are recognized as being paramount in designing new product. In consequence, systems engineering is an interdisciplinary method that develops and exploits structured efficient approaches to analysis and design complex

engineering problems. This focuses more on constructs of analysis and synthesis for problems involving multiple realistic aspects to enable the realization of successful products. Since systems engineering deals with the methodology rather than physical manifestations of science, its description considers both the business and the technical needs of customers with the goal of providing a quality product that meets the user needs. Therefore, Systems engineering covers a broad set of processes and methods for modeling and analyzing interactions among the requirements, subsystems, constraints and components that make up a product. Its purpose is to improve an organization's understanding of the product as a whole, and to use that total product understanding to better optimize the tradeoffs that drive detailed design, manufacturing, service decisions and so on throughout the product lifecycle. However, the following aspects of real time specification, for instance, have still not properly been addressed in existing building design methods such as:

1. Transformation of an operational need into a description of system performance parameters and a system configuration through the use of an iterative process of evaluation aspects
2. Integration of related technical parameters and ensure compatibility of all related, functional and program interfaces in a manner that optimizes the total system definition and design.
3. Integration of reliability, maintainability, safety, survivability, human and other such factors into the total technical engineering effort to meet cost, schedule and technical performance objectives.

This paper deals with a tentative application of systems engineering (SE) concepts to the building design process. As SE is an open process, a major advantage for this application could be a proposed approach with various technologies, business and management aspects that could be efficiently evaluated. This is advantageous because an open process can be applicable to any application domain, as long as these applications adhere to fundamental principles.

SE standards have been preliminary successful because their concepts involve new technologies and requirements management approach needed for:

- Definition of systems, including identification of costumer requirements and technological specifications;
- Development of systems, including conceptual architecture, tradeoff of design concepts, configuration management during design development, and integrated product and process development;
- Deployment of systems, including operational test and evaluation, maintenance over an extended lifecycle, and reengineering (renovation).

Modern systems engineering, including both products and services, is often very knowledge intensive. In accordance with systems engineering, *EIA-632* standard (EIA-632, 1998) a method for adapting the process of such a standard to the conceptual architecture for a building design is applied with implementation and evaluation of different phases defined in design process. As a result, building performance specifications, preliminary/detail designs, building prototype build, components tests and subsystem/system integration tests are conducted in sequence to apply the SE concepts to the building design process.

## SYSTEMS ENGINEERING: OVERVIEW

Since systems engineering is the discipline that emphasizes the development and exploitation of structured, efficient approaches to analysis and design, tools for analyzing and optimizing the performance and cost of a product, as well as methodologies for the process design and analysis are fundamental. For example, the definition, design and realization of a new building requires a product design which can be advanced in performance, safety, ergonomics, minimal cost, … etc. But the process of efficiency developing that design and implementation models, prototypes and test methods is also critical for timely building introduction and reduced development cost. Systems engineering can skill such as concurrent engineering design, hierarchical modeling, and other provide profound value to buildings definition and development.

Uncertainties in the success and time requirements of the development process underscore the importance of the reliability of building design and the importance of risk assessment (for cost and time estimation). Furthermore, the reliability of the building, together with its performance and costs (including maintenance) and its life cycle, contribute strongly to the value of the systems engineering products. Hence, life cycle considerations overlaid on the design process and building quality place a premium on reliability and risk assessment.

The efficiency of SE concepts is defined by methods, algorithms and tools used in the most complex of design problems. This methodology includes elements such as systems response functions, trade-off analysis, specifications and performance metrics, optimization techniques in the presence of various sorts of constraints, marginal and sensibility analysis, utility theory, scheduling, control databases, cost estimation, decision analysis, modeling and simulation, and software environments and tools. Although, SE model is an interdisciplinary area in which its conception affects all kinds of projects, a good description of systems engineering applies to systems as simple as a toaster and as complex as environmental restoration. The only difference between these two extremes is the degree of formality with which each process is used. Consequently, a model of systems engineering is a diagram that includes the known processes that we do. However, there are many models of popular systems engineering standards, such as: *ISO-15288*, *ANSI/EIA-632*, *IEEE-1220*, *SP-6105*, *ECSS-E-10A*, but their diagrams are quite similar to each other (Sheard et al. 1998).

The *EIA-632* standard is chosen, in this paper as an appropriate model for building design process; because it has an extra phase that involves the aggregation of end products. The figure 1 shows the basic SE model of this standard, which has four main categories of processes, as:

- Technical Management Process – Processes that plan, assess, and control the systems engineering process.
- Acquisition & Supply Process – Processes that supply and acquire aspects of the system.
- System Design Process – Processes used to define requirements and design solutions for the system.
- Product Realization Process - Processes used to implement and the product produced by the system and to facilitate its transition to use.

- Technical Support Process -Processes used to analyze the system, to validate requirements, and to verify the system, and to validate other end products.

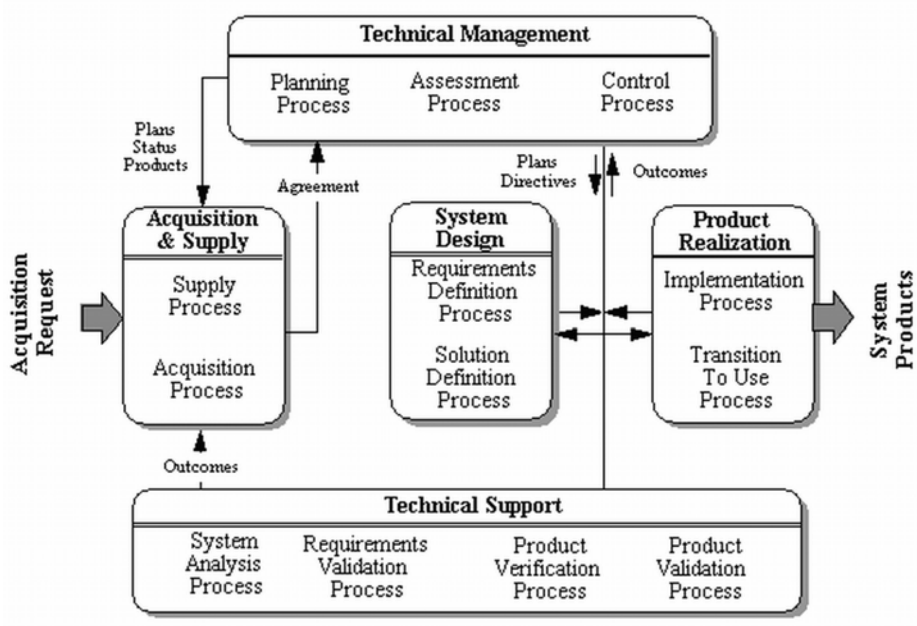


**Figure 1.** Processes of systems engineering

The relationship between the input and output procedures of this model represents the forward movement of a system development. There are also loops that interact to represent the development repetition that is common in complex systems. Alternatively, a life cycle of this SE model is organized into phases that begin when a product is conceived and end when it is no longer available for use.

**Conception of Design Phases**

Different phases in the development process are usually known by descriptive names such as conceptual design, preliminary design and detail design. Through this consideration, the design engineering process is focused on the development phases of the product life cycle. Furthermore, all phases are considered during design, such as productivity or user agreement. The initial process definition covers the activities following the need definition and approval to proceed with design during initial agreement by users. Restoration phases are added in subsystem updates. It is during the period defined from approval to acquisition tasks that the general concept is created. The design development period is principally organized into similar phases where the design fidelity increases, uncertainties are reduced and attributes of the product are established. In most cases, design phases are then well described by activities performed and design data products are produced by the end of the phase. The phase transition products are described by Blanchard (1998) as baselines with specific content and level of detail.

- Phase of the feasibility study is a conceptual design related to functional baseline (system specification) and design in which their activities are requirements analysis; evaluation of feasible technology applications and selection of technical approach.

- Phase of the preliminary design or system development is an allocated baseline (e.g. development, process and material specifications) in which their activities are requirements allocation; trade-off studies and synthesis.
- Phase of the detail design or system operation is a product baseline (e.g. produce and build to prototype in which their activities are based on subsystem design; development of engineering models; verification of manufacturing and production processes.

The standard of EAI-632 describes three stages of maturity for the design specifications: conceptual, initial and established. Conceptual specifications are used to show the feasibility of a higher-level product. Initial specifications are used to direct lower-level developments of subsystems. Established specifications provide guidance to testers, provide a basis for negotiation of engineering changes, and enable configuration management of solution definitions.

The process always begins with defining and documenting the customer's needs. A useful method for applying this is quality function deployment (QFD). This consists of a chart called the "house of quality". After the customer's needs are determined the design goes through successive generations as the design cycle is repeated (Chapman, 1992). The requirements are set and a model or prototype is created. Each validation of a model or test of a prototype provides key information for refining the requirements.

**BUILDING DESIGN PROCESS**

Building process is the acquisition of a system as an end product. The process begins with the necessity of a building requested by the customer. The process begins with a feasibility study. Financial budget, site conditions, compulsory regulations, clients needs together with the design requirements are defined during the feasibility search. The architectural program is structured at the end of feasibility. During development of architectural program, the issues that affect the design together with architectural aspects (building type, spatial requirements, etc.), environmental aspects (site, location, surroundings, climatic conditions, etc.), and regular aspects (codes and standards) are also taken into account. All-previous steps are considered as the pre-design phase. In other industries, including building construction, design plays an essential role in the efficiency of productive process and in the production of value to the clients (Fabricio et al. 1999). The design process may be divided into a few stages based on the level that each stage is expected. Nevertheless, whatever the stages are; at the end, the output includes the specification documents that satisfy all the requirements needed for design and construction. Based on this information, construction process executes till the building acquired. During the life cycle of the building in use, the feedback for maintenance and renovations are used for the expected modifications in daily necessities. The process is continuously cycling and never ends but feeds the new requirements for a new design problem and starts from scratch. Furthermore, each stage in the process is nonlinear and has feedback cycles, which strengthen the whole process with minimum uncertainty at the end product. Figure 2 shows the schematic illustration of the building design process with its different phases.

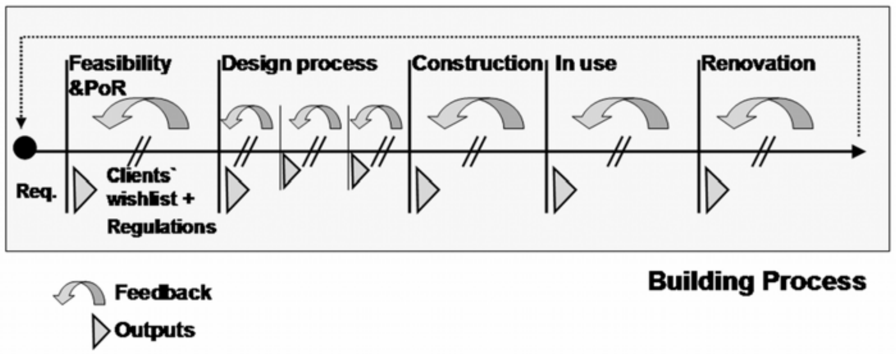


**Figure 2.** Building design process

In most cases, design process can be simplified as the function of the inputs, limitations, methodologies and outputs. Methodologies describe how to execute the process. In the building design process, the inputs can be outlined as ideas and necessities, and the outputs as products (usually buildings. It is shown in figure 3, that design process might be conducted of limitations relating to regulations, client's needs, cost, and time; and of methodologies in form of organizations, tools and techniques.

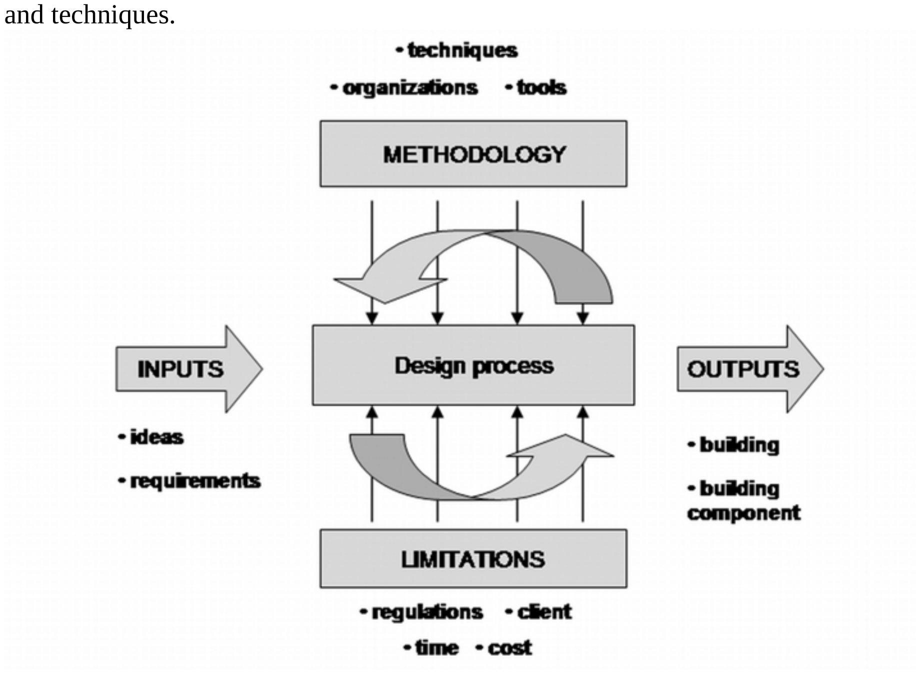


**Figure 3.** Simplified elements of design process

For instance, Fabricio (et al., 1999) mentioned an important perspective on building. This has the purpose of characterizing the design process as a sequential conversion view that transforms the information from technical standards and requirements into solutions and product specifications.

**APPLYING SYSTEMS ENGINEERING MODEL TO BUILDING DESIGN**

The objective of building design is to build a successful high-performance building. To achieve this goal, an application of the integrated design approach to the project during the planning and programming phases is mandatory. The fundamental challenge of buildings design is that all building systems are interdependent. To closely interact throughout the building design process, it is necessary that the building design process comprises the following steps:

1. Define and identify the customer's requirements (or stakeholders)
2. Create alternative design concepts that might satisfy these requirements
3. Build, validate, and simulate a model of each system design concept.
4. Select the best concept by doing a trade-off analysis.
5. Update the customer requirements based on experience with the models.
6. Build and test a prototype and update the customer requirements.
7. Build and test a pre-design version of the building and validate the process.
8. Update the customer requirements based on experience of last analysis.
9. Build and test a design version of the building and than deliver it

Figure 4 illustrates a schematic approach of adapting a systems engineering model to the building design process. Then a typical systems engineering layout, which is the basic concept of the EIA-632 standard, for the application of the development of, systems design engineering, is used to expand the building process.

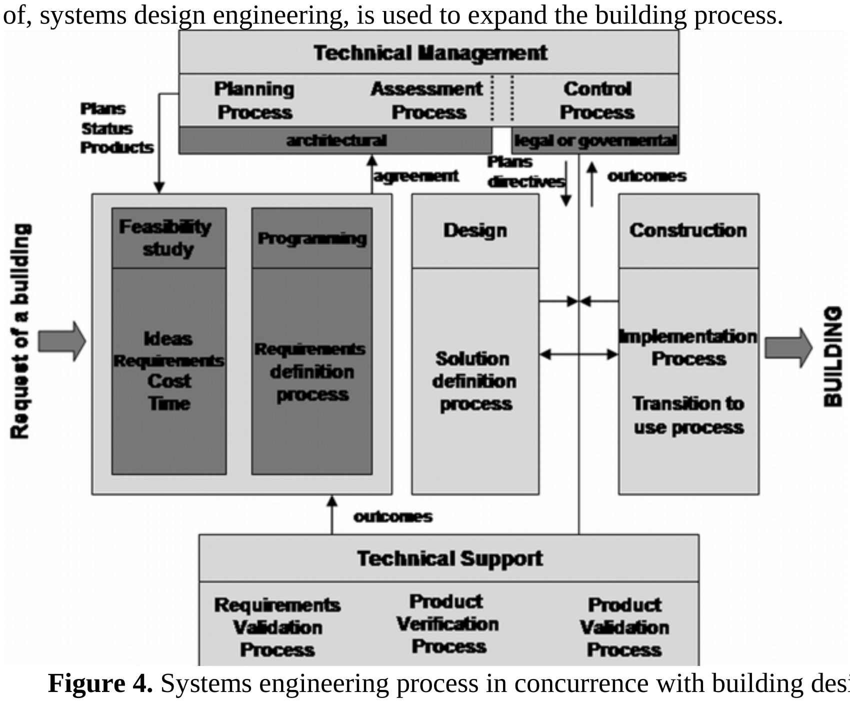


**Figure 4.** Systems engineering process in concurrence with building design

All steps described above can be depicted graphically on a Spiral diagram, a Waterfall model, a V cycle, etc. Indeed, the V-shaped life cycle is a sequential path of execution of processes. Each phase must be completed before the next phase begins. Testing is emphasized in this model more so than the waterfall model though. The testing procedures are developed early in the life cycle before any coding is done, during each of the phases preceding implementation. Figure 5 shows the schematic diagram of systems engineering combined with different phases based on the development of the building design. This illustrates a complete understanding of applying systems engineering concept to building design process.

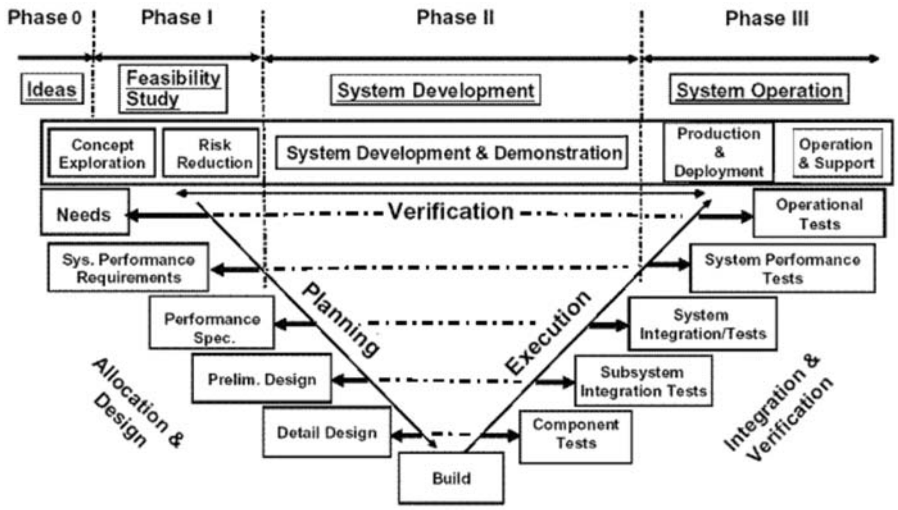


**Figure 5.** Building design process in form of V-shaped life cycle

Figure 5 highlights the interactions that take place between the links of planning or decomposition (\) and execution or construction (/) of the system. When the cycle V is applied to all the components of a system (see figure 6), the number of loops can easily be deduced by decomposing and reconstructing the design concept.

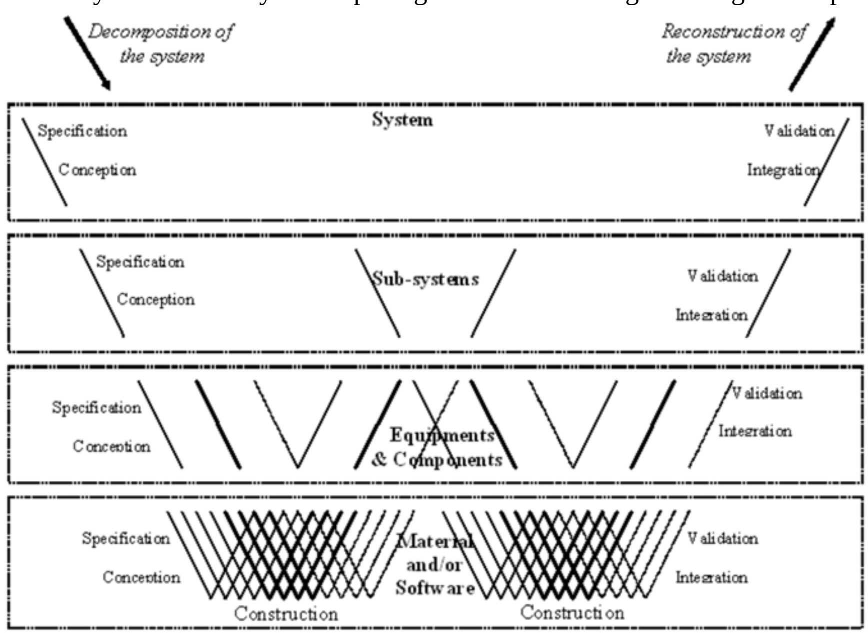


**Figure 6.** Sequences of V cycles for the development of a system (Building)

A building architecture is a hierarchical framework for the structure of a system (building). Since a building can be a complex system, this system is decomposed into sub-systems and eventually component-level "chunks" that can be handled by individual team. Each phase in every V cycle is reviewed and finalized before handled over to the next design team. The system is then physically reconstructed from its individual components into sub-systems and eventually integrated into a complete system (building). Plans are in fact created to ensure that the sub-systems and the overall system perform as designed (verification) and ultimately meet the desired intent of the costumer (validation) by performing the desired functions.

**On Verification and Validation**

In V&V, it requires to determine whether the system built satisfies all system requirements. V&V processes are conducted during the project life cycle to ensure that a project meets the defined mission by fulfilling the identified functions and requirements (e.g. Sahraoui at al. 1999). This involves two different approaches:

- Validation focuses strictly on the requirements and ensures the right problem has been defined.
- Verification focuses on the design solution for the validated requirements and ensures that the problem is solved.

Although the EIA 632 standard is applied for building design process in this study, eight requirements for V&V are contained and evaluated in this standard. Figure 7 illustrates different V&V activities with respect to development of the V diagram.

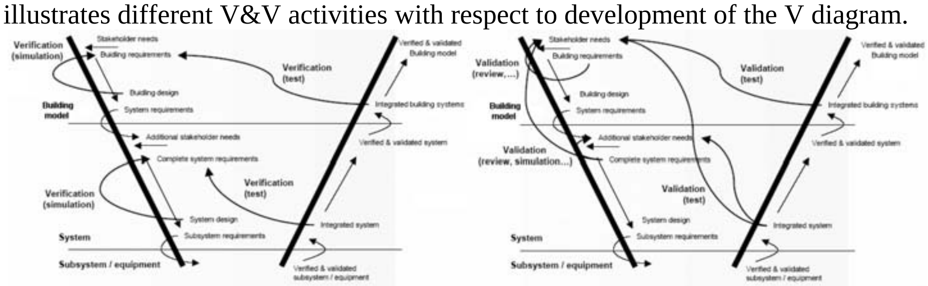


**Figure 7.** Verification and Validation activities

**Traceability Issues**

Another way of describing V&V is that verification is "constructing the building model right" and validation is "constructing the right building model." It is important to recognize that every requirement should be traced in the system to its realising component(s), and vice versa from components to requirements. One way to do this is through a *requirements traceability matrix*, as shown in figure 7.

| Req. | Spec.Si | Design Di | S/w modules | |
|---|---|---|---|---|
| R1 | | | | |
| R2 | | **X** | | |
| Rn | **N/A** | | | |

X : relational link between a requirement and a design

N/A : Non applicable *(no apparent link)*

**Figure 8.** Traceability table between requirements and functions

Safety requirements traceability approach has been proposed in (Mathers et al. 2000) for complex avionics systems. Few tools have been designed to overcome this aspect. However a formal notation for requirement enables to propose a preliminary approach to such issue.

**CASE STUDY: BUILDING DESIGN**

For example, if a building model is considered two operational functions are sub-systems of this model and heating, lighting power, waste, water and security are components of this model. To build the building model capturing all the necessary information an expressive modeling technique supporting hierarchies (abstractions) and several different views of a design are required. “Systems decomposition” skill, a method based on breaking the building model down to smaller and smaller parts until they can be easily understood and their performance easily modeled and subsequently verified. In figure 8, a classical functional analysis for systems decomposition is applied to breakdown a building model in order to detail specifications and design development followed by components, sub-systems and systems verification. An optimized design for conducting trade studies when the cause and effect relationship between parameters and outcomes can be specified, in this case mathematically or through a simulation. In fact, optimization techniques are extremely useful for investigating sensitivity to key building design parameters.

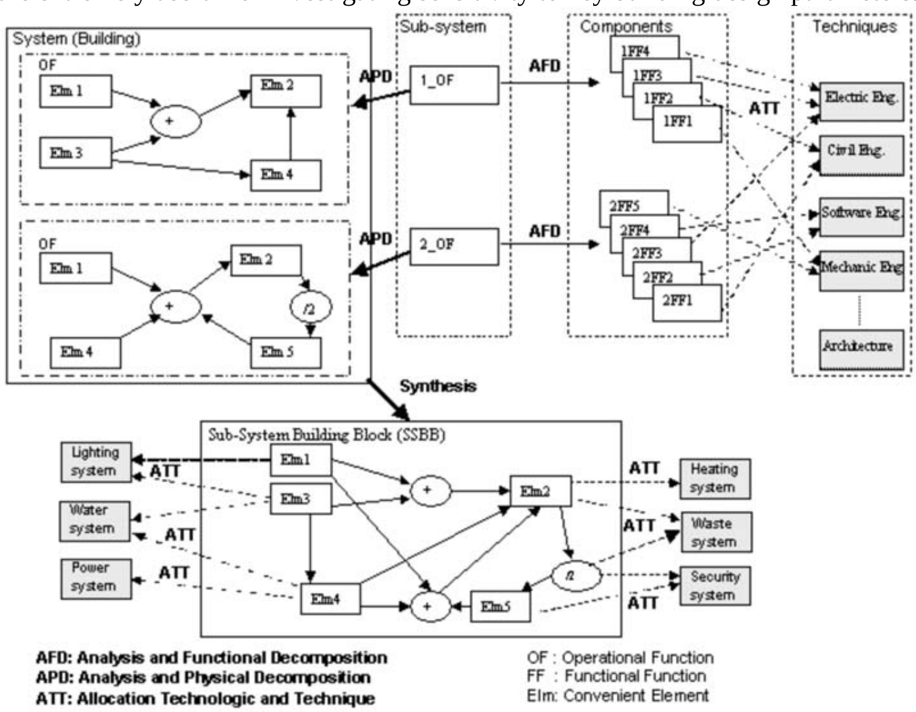


**Figure 6.** Building model functional breakdown

Functional function may be achieved by software, hardware, a human interaction, etc. The goal at this stage is to address what functions needed. Convenient function is an operation of the action that system must perform to accomplish its purpose.

Functional analysis is the interactive process of breaking down, or decomposing requirements from the system level, to the sub-system, and as far down the hierarchical structure as necessary to identify specific components of the system.

## CONCLUSION

The feasibilities of both business costs and operation models applied for building design are developed through an adapted systems engineering procedure. Then, this new approach is theoretically justified through a schematic approach of adapting a systems engineering concept to the building design, which uses modeling techniques and tools in combining with a V cycle for system decomposition. In fact, systems engineering drives process tools to translate the user's desired capabilities into a structured system of interrelated design specifications. It is an iterative task, performed within a disciplined framework to maintain the desired operational capabilities within constraints.

As part of a conceptual design of the initial portioning of the system into sub-system and initial technical/performance issues are discussed. The results of the building design process serve to define good requirements. Then, a conceptual building design can be used to develop a technical specification (usually called a document of specification requirements). This is important issue concerning this perspective in building, there may be benefits in making a common document of specification requirements based on a trade-off between cost, schedule and requirements in order to realize a building project with at least both significant aspects: lower cost and customer satisfaction.

## REFERENCES


BLANCHARD, B. S. (1998), *Systems Engineering Management*, 2nd Ed. John Wiley and Sons, Inc.

EIA-632, (1998), Processes for Engineering a System", ANSI/EIA-632, EIA.

CHAPMAN, W. L., BAHILL, A. T., and WYMORE, A. W. (1992), *Engineering Modeling and Design;* CRC Press, Boca Raton, FL.

FABRICIO, M. M., MELHADO, S. B. and BAIA, J. L. (1999), Brief reflection on improvement of design process efficiency in Brazilian building projects, *in Proc of IGCL-7*, pp. 345-356, University of California, USA

HUNSTAD, A. and HALLBERG, J. (2002), Design for securability-Applying engineering principles to the design of security architectures, in *Proc of WAEPSSD*, Massachusetts, USA.

HOANG, N., JENKINS, M., KARANGELEN, N. (1996), Data Integration for Military Systems Engineering, *in Proc of IEEE Symposium and Workshop on Engineering of Computer Based Systems*, USA.

MATHERS, G. AND SIMPSON, K. J. (2000), Framework for the Application of Systems Engineering in the Commercial Aircraft Domain, DRAFT Version 1.2a American Institute for Aeronautics and Astronautics, USA

SHISHKO, R, (1995), NASA Systems Engineering Handbook, *NASA*,USA

SHEARD, S. A. and LAKE, J. G. (1998), Systems Engineering Standards and Models Compared, in *Proc of 8th Symposium of INCOSE*, Vancouver, Columbia.

SAHRAOUI, A.E.K. and JONES, D. (1999), Validation & verification: towards a system engineering framework, in *proc of 13th International Conference on Systems Engineering* (ISCE'99), Las Vegas, USA