DEVELOPING A STRUCTURED APPROACH WITH SYSTEMS ENGINEERING TO THE BUILDING DESIGN

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Abstract

The development in the design process is usually based on the choice of a method for designing the system, in which this method is frequently faced with tightening environmental requirements, reducing development cycle times and growing complexity. To tackle such factors, the paper proposes a comprehensive approach focusing on applying systems engineering approach to the building design support. In particular, this paper addresses all capabilities of using some available systems engineering standards (like EIA-632) in the design process. Then, a methodological approach is proposed for the practice of requirements engineering by applying quality assessment and control to design in early phase. The paradigm used, here is to extend and particularly to adapt the work carried out in military and space systems to modern building services by taking into account the semantics of buildings in terms of different engineering fields and architecture issues.

Keywords: Systems engineering, building design support, validation and verification.

1. Introduction

The systems engineering approach was primarily developed by the military industries as a process by which large engineering projects could be designed, implemented, and tested prior to deployment [3]. This approach is based on a structured method towards specification, design, acquisition, integration, reengineering, and implementation of a complex system over its life cycle. Systems engineering (SE) has emerged as a distinct professional discipline since the late nineties in response to the ever-increasing complexity of new products and systems of different fields. Eventually, this emergent discipline has been applied with success mainly to scale complex systems and projects in the following industries: aeronautic [10], automobile 6] and space [7], etc. For the building domain, there is a great interest in applying such a good practice in the building design process and particularly manufacturing and production systems.

In this case, 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

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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 means needed for:

- Definition of systems, including identification of costumer requirements and technological specifications;
- Development of systems, including conceptual architecture, trade-off of design concepts, configuration management during design development, and integrated product and process development;
- Deployment of systems, including operational test and evaluation, maintenance over 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 [2] 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.

The remainder of this paper is organized as follows: the next section describes building design process. Then it follows systems engineering and deployment according to context and application. This is followed by an application of systems engineering to building design process, and finally conclusion.

2. Building design support

Building design 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 (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 [4]. 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 1 shows the schematic illustration of the building design process with its different phases.

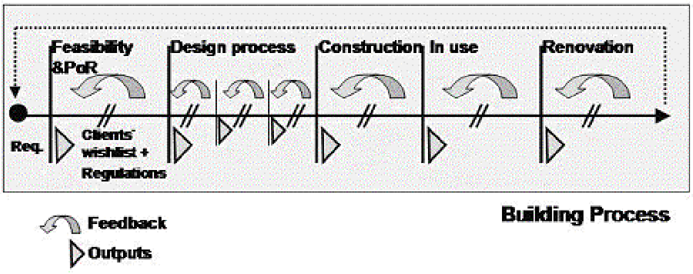

Figure 1. Building design process

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. It is shown in figure 2 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.

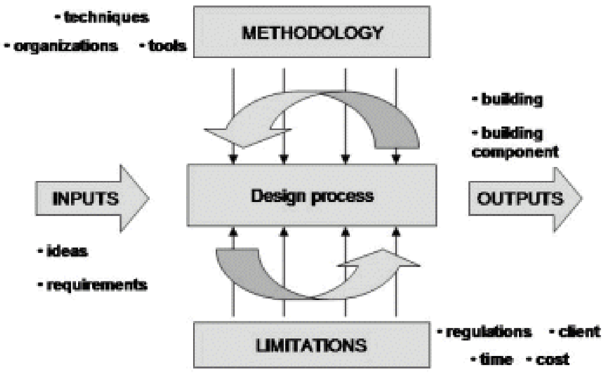

Figure 2. Simplified elements of building design process

For instance, Fabricio [4] 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.

3. System Engineering and Deployment

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 apply skills to concurrent engineering design, hierarchical modeling, and to buildings application and development as well. 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 similar to each other [8]. 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 basics of SE model, which has four main categories of processes, are:

- Technical Management Process – Processes that plan, assess, and control the systems engineering process.
- Acquisition and Supply Process – Processes that supply and acquire aspects of the entire 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.

3.1 Systems engineering and processes

The SE Framework Multidisciplinary teamwork ensures the accuracy and completeness of the evolving technical data package from which test articles, pre-production prototypes, and production products are to be manufactured or coded. The generic modem is shown in figure 3 (systems engineering standard EIA-632).

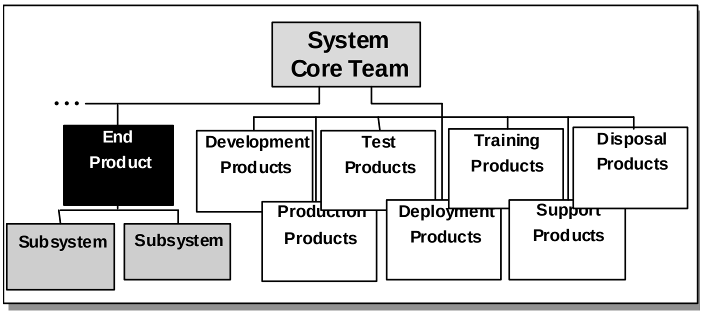

Figure 3. Processes of systems engineering

3.2 Systems of systems

The deployment of SE product can be carried out in a comprehensive approach by separating the final product (the building) from the enabling product (production systems: crane, etc.) and development product (simulation tools, etc.) this can be best illustrated by the following figure 4. A single block will really define the complete solution to a complex problem more typical of the design project. When an end product sub-system requires further development it will have its own subordinate building block. Once the descriptions of the end product of the initial building block are completed, and preliminary descriptions of the end product subsystems are defined, the development of the next lower layer of building block can be initiated. If the building block has reached the "button", the design of these items requires no-development (i.e. all enabling product for that end product already exist and are all compatible with each other and with total solution).

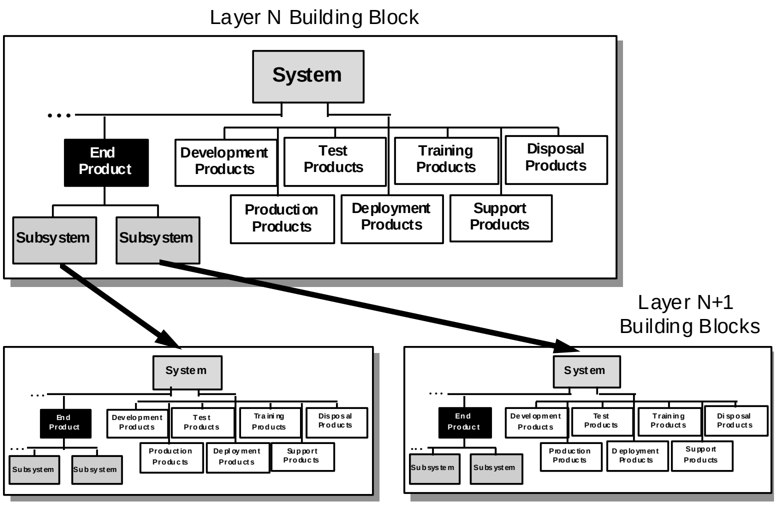

Figure 4. Hierarchy of building blocks

4. Context, problematic and state of the art

4.1 Systems of systems

The context in this work is related to building services. The integration of Building Science Engineering, Architecture, Construction Management and Risk Assessment Services for new construction projects and existing buildings becomes a must. Building a systems require a lifecycle of development as shown in figure 5.

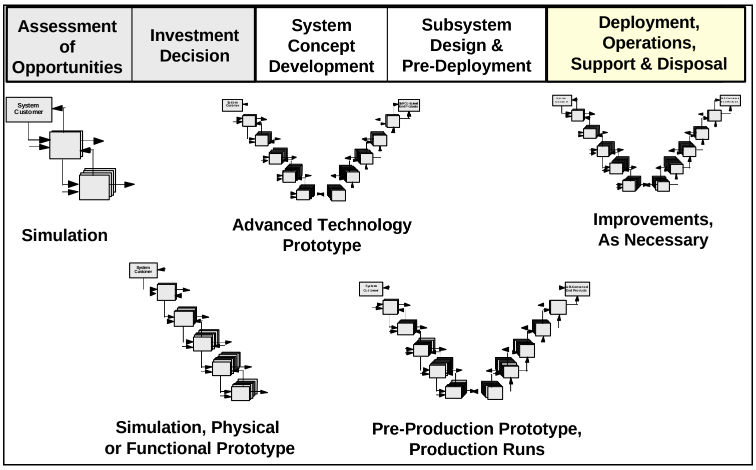

Figure 5. Enterprise-based life cycle phases

We are concerned in our context from the systems development (including subsystems design and deployment operation) the deployment operations concerns the multiple development and implementation of the initial system as a final system or a prototype.

4.2 Problem Statement and State of The Art

There are numerous approaches to integration of technologies. However, a comprehensive approach where to see a building as a systems by itself. Such systems to be built needs requirements ranging from users/stakeholders requirements to institutions, standards, local, national regulations, etc, where is the limit of such integration if a global approach is not used. We focus in this work on the problematic of integrating advanced techniques in control supported by IT (information technology) tools to monitor an optimal design.

Up to our knowledge there are not yet establishment methodologies and approaches linking systems engineering (SE) and building HVAC (Heating, Ventilation and Air-Conditioning) systems and other components. Nevertheless, few energy research departments in America, like for example the US Department of Energy [1] use systems engineering to home building as advanced framing and insulation methods to increase efficiency and comfort while decreasing energy costs.

5. Applying SE Environment to Building Design Process

From previous sections, it is clear that engineering a system using systems thinking and systems approach is the right way in analyzing and resolving a problem or in developing a product (or a system). In contrast, the systems engineering process, which has been proved successful in other industries, is believed to be applicable to the management of this systems issue. The ultimate 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 comprise 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 6 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.

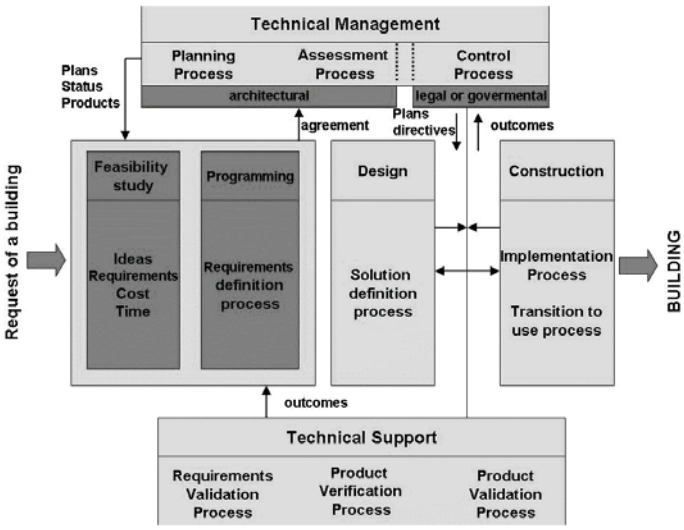

Figure 6. Systems engineering process in concurrence with building design

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 system before any coding is done, during each of the phases preceding implementation.

5.1 Systems engineering approach as analysis-synthesis

The SE process, which specifies functions, sequence and the interrelationships between various stages of the systems engineering process is extremely imperative so that its application is successful. Although, there exists several diagram models (spiral, waterfall, V, etc.) that are used for applications, the V (or *Vee*) diagram, which relates systems engineering to project lifecycle, is probably the most popular one that is used for the application of processes for systems engineering concepts. Figure7 shows the schematic diagram of systems engineering combined with different phases based on the development of the building design in a form of V diagram, originally due to [5]. Through a functional decomposition (or analysis), detailed design, and physical assembly; we can specify the whole, its parts, and their interactions clearly and at all decomposition scales. The subsystems at intermediate levels are crucial for managing complex systems, for they enable us to introduce complex details one step at a time.

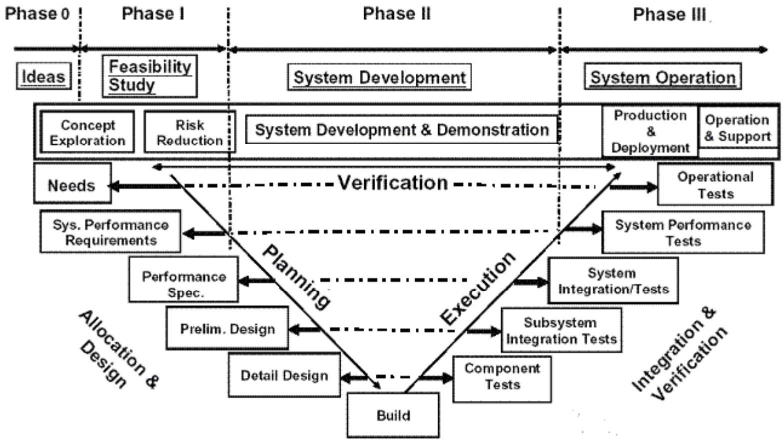

Figure 7. Building design process in form of V-shaped life cycle

The SE process begins with eliciting stakeholder requirements and ends with acceptance tests where the final product is validated against the original stakeholder requirements. Through system development, verification is carried out at every stage to ensure that the intermediate developments meet all requirements and specifications, which have been set at the previous stages. But, system requirements have to be traced to user requirements to show that all user system requirements are indispensable. Generally, the traceability is created from the lowest level of user requirements to an intermediate level in system requirements. In short, figure 7 highlights the interactions that take place between the links of decomposition or analysis (\) and of construction, which means physical integration, or synthesis (/) of the system.

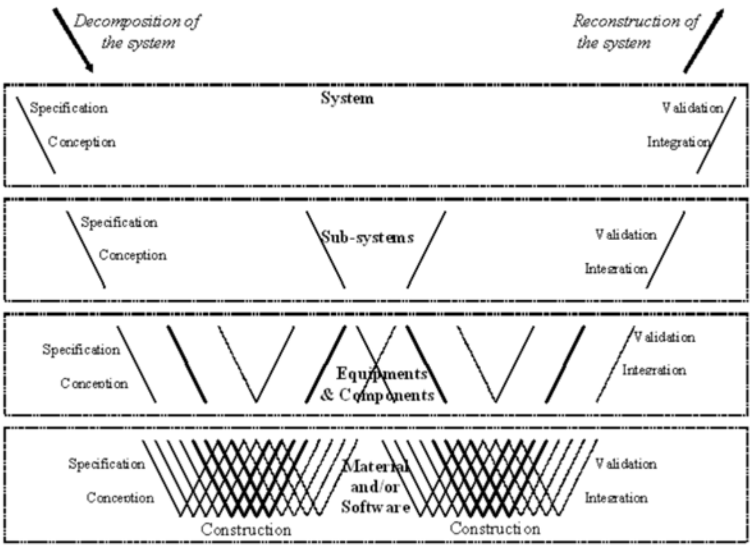

Figure 8. Sequences of V cycles for the development of a system (building)

When the V cycle is applied to all the components of a system (see figure 8), the number of loops can easily be deduced by decomposing and reconstructing the design concept. A building architecture is a hierarchical framework for the structure of that 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 it is 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.

5.2 On Verification and Validation (V&V)

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 [9]. This involves two different approaches: (1) validation focuses strictly on the requirements and ensures the right problem has been defined; and (2) 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 9 illustrates different V&V activities with respect to development of the V diagram.

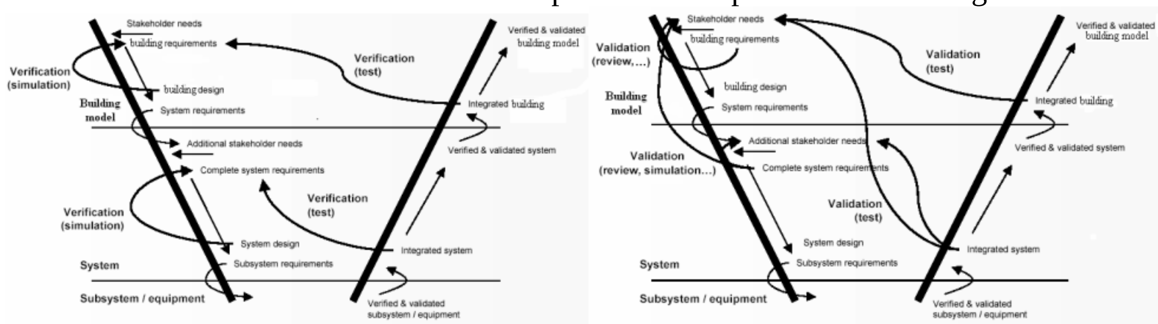

Figure 9. Verification and Validation activities

5.3 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 realizing component(s), and vice versa from components to requirements. One-way to do this is through a *requirements traceability matrix*, as shown in figure 10.

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 10. Traceability table between requirements and functions

6. 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. 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 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 specification requirements document). 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 to realize a building project with at least both significant aspects: lower cost and client's needs.

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