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DESIGN AS LEARNING

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Abstract

This paper explores the knowledge creation process - not only scientific or technological - which takes place through the engineering design process. To this end, we go beyond the traditional conception of design, which conceives it as a transformation of information, and we propose to consider it as a process of knowledge creation and learning.

Contrary to the behaviourist theories, we assume Ausubel's approach of meaningful learning which considers knowledge as something that takes place exclusively in a conscious human mind through a process of interpretation, construction and elaboration. As a theoretical framework we draw on the Bloom´s Taxonomy for Learning as updated by Anderson & Krathwohl, which provides us with a proper conceptualization of different types of knowledge and cognitive processes.

As an empirical reference to support the analysis, we use the *System Engineering Standards* for space projects of the European Space Agency. This kind of projects are expected to be complex, high technology and innovative enough to constitute a privileged case study to examine the knowledge creation process which takes place within engineering design.

Our main contribution is to argue that all different types of knowledge and cognitive processes which constitute learning, are inherently present at different stages of design process. This allows us to consider the engineering design activity as a learning process, which is expected to have important consequences both practical and theoretical.

Key words: Design process, knowledge, learning.

1 Introduction

According to the latest socio-economic theories, knowledge is the basic organization asset that enables action and growth in our current changing and complex societies. In this way, the capability to learn turns out to be the only sustainable advantage for organizations to survive [1].

Particularly, engineering organizations develop learning through projects and especially through new product design projects [2], [3], [4]. Therefore, projects are seen as the right instrument to develop not only new organizational knowledge but also new technical and technological knowledge. Moreover, innovation establishes the foundations of the necessity to enhance the creation of new knowledge through the design process.

Concerning this issue, there are several precedents which we have classified into inter-project learning studies, focused on how knowledge can be transferred from one project to another, and intra-project learning studies, oriented towards understanding how knowledge is built during the design process in order to solve each specific, and often uncertain, problem.

Regarding inter-project learning studies, it is important to highlight the research for reusing knowledge [5], structuring and indexing knowledge [6], [7], [8] and identifying knowledge sources for design [9], [10]. In addition, there are several studies in the field of project management which focus on forward planning [11], characterizing organizational learning in design [12], analyze influence of cultural issues [13], discussing bearers and barriers for knowledge transference [4], learning organization based on projects [14], learning strategies in engineering projects [15] and managing knowledge and previous experiences in projects [16].

On the other hand, intra-project learning studies are devoted to the analysis of knowledge management focused on individuals [17], [18], learning arenas and processes within the project [19], tacit knowledge in projects [20], organization of the project to enhance learning for innovation [2], knowledge creation models [21], learning architectures [22] and learning methods in projects [23].

Taking into account all this studies, the aim of this paper is to provide a solid theoretical foundation for the conception of engineering design as a learning process. To this end, we will get an insight into learning theories in order to contrast them within the framework of engineering projects.

2 Conceptualization of knowledge and learning

In order to clarify the theoretical approach of this study, it is important to make explicit the difference between information and knowledge. Contrary to the behaviourist theories, we assume Ausubel's approach to meaningful learning [24] which considers knowledge as something that takes place exclusively in a conscious human mind. Furthermore, we assume an approach widely accepted among researchers [2], [17], [18], [19], [20] in which knowledge is considered to be built through a process of interpretation, construction and elaboration; but never through an aseptic transference of information.

In this way, we consider information as a set of data gathered in a specific format which, through interpretation, may increase, rearrange or modify previous knowledge in the individual [25]; for this reason, information can be conceived as the raw material for knowledge creation.

On the other hand, according to the cognitive paradigm, knowledge is considered to be placed in the subjective world of the person. For this reason, learning would be the process in which the individual contextualize information and builds a new meaning from it. In this process, meaningful learning takes place when the individual establishes a link between new information received and ideas which are already known. According to this approach, learning would be a process for the construction of meanings which are idiosyncratic.

2.1 Types of knowledge and cognitive processes

As a theoretical framework for the analysis of the engineering design process from the learning perspective, we draw on the Bloom´s Taxonomy for Learning as updated by Anderson & Krathwohl [26] to take into account the organizational level of learning. This provides us with an adequate conceptual reference to perform a deep interpretation of the issue. Specifically, we carry out our analysis on the basis of two main concepts to understand learning processes: knowledge, or what the person knows or is able to know, and cognitive processes, or how the person thinks while constructing new meanings, or knowledge.

According to this proposal, **knowledge** would be classified into four categories:

A. **Factual knowledge** is knowledge of discrete, isolated content elements (i.e. terms and facts), which encompasses the basic elements that experts use in communicating about their academic discipline, understanding it and organizing it systematically.

   Subtypes: 1) Terminology; 2) Specific details and elements.

B. **Conceptual knowledge** includes knowledge of categories and classifications and the relationships between and among them. It includes schemas, mental models, or implicit and explicit theories accounting for a certain set of phenomena.

   Subtypes: 1) Classifications and categories; 2) Principles and generalizations; 3) Theories, models and structures.

C. **Procedural knowledge** is the knowledge of how to do something, which might range from completing fairly routine exercises to solving novel problems. It often takes the form of a sequence of steps to be followed. It includes knowledge of skill, algorithms, techniques and methods, collectively known as procedures. Procedural knowledge also includes knowledge of the criteria used to determine when to use various procedures. Whereas factual and conceptual knowledge are referred to objects and phenomena, procedural knowledge reflects knowledge of different processes.

   Subtypes: 1) Subject-specific skills and algorithms; 2) Subject-specific techniques and methods; 3) Criteria for determining when to use appropriate procedures.

D. **Metacognitive knowledge** is knowledge about cognition in general as well as awareness of and knowledge about one's own cognition. In consequence, it includes knowledge of cognition and knowledge for monitoring, control and regulation of cognition.

   Subtypes: 1) Strategic knowledge; 2) Knowledge about cognitive tasks, including contextual and conditional knowledge; 3) Self-knowledge.

In addition, **cognitive processes** involved in learning would be the following ones:

1. **Remember**: Retrieve relevant knowledge from long-term memory. The relevant knowledge may be factual, conceptual, procedural or metacognitive, or some combination of these. Remembering knowledge is essential for meaningful learning and problem solving as that knowledge is used in more complex tasks.

   Subcategories: 1) Recognizing; 2) Recalling.

2. **Understand**: It is the process of constructing meanings from information received at a certain context. It includes the capability to change from one form of representation to another, to find a specific example or illustration of a concept or principle, to determine that something belongs to a certain category, to abstract a general theme, to draw a logical conclusion from presented information, to detect correspondences between ideas or objects and to construct cause-and-effect models.

   Subcategories: 1) Interpreting; 2) Exemplifying; 3) Classifying; 4) Summarizing; 5) Inferring; 6) Comparing; 7) Explaining.

3. **Apply**: Carry out or use a procedure in a given situation. It means applying a procedure both to familiar and unfamiliar tasks.

   Subcategories: 1) Executing; 2) Implementing;

4. **Analyze**: Break material into its constituent parts and determine how the parts relate to one another and to an overall structure or purpose. It includes distinguishing relevant from irrelevant parts or important from unimportant parts, determining how elements fit or function within a structure and determine a point of view, bias, values or intend under presented information.

   Subcategories: 1) Differentiating; 2) Organizing; 3) Attributing.

5. **Evaluate**: Make judgements based on criteria and standards. It involves detecting inconsistencies or fallacies within a process or system and external criteria.

   Subcategories: 1) Checking; 2) Critiquing.

6. **Create**: Put elements together to form a coherent or functional whole; reorganize elements into a new pattern or structure. It means to coming up with alternative hypothesis based on criteria, devising a procedure for accomplishing some task and inventing a new system.

   Subcategories: 1) Generating; 2) Planning; 3) Producing.

3 The engineering process at ESA projects (2)

Within the framework of the space projects of the Eurpean Space Agency, the engineering domain is described in several standards concerning *Space Engineering* [27], [28]. This is a specific domain of the space projects whose characterization relies on three basic notions:

1. The **system engineering process**, including those processes which are exercised iteratively through the project in order to design and verify a product which meets the customer requirements.
2. The **engineering disciplines** (electrical, mechanical, software, communications…) that contribute their expertise to the engineering process, which is considered to be a multidisciplinary activity.
3. The **levels of decomposition** at which the engineering process is being exercised (system, subsystem, set, equipment/software product, assembly and part).

Each cell of the Figure 1 represents a potential project engineering activity. The activities on the system engineering process axis should not be confused with the phases in the project life cycle. Rather, they should be thought of as activities in a process which may need to be iterated several times during the course of a project, in order to achieve a satisfactory outcome at each stage.

The way in which these activities are arranged, their relative importance and the amount of effort devoted to each activity will vary according to the type of project, its complexity and the extent of the technological advance and innovation required to implement it; generally, however, each activity should be considered and exercised concurrently during each project phase, with its relative importance adjusted appropriately, so that the downstream implications of each decision are fully assessed and recognized.

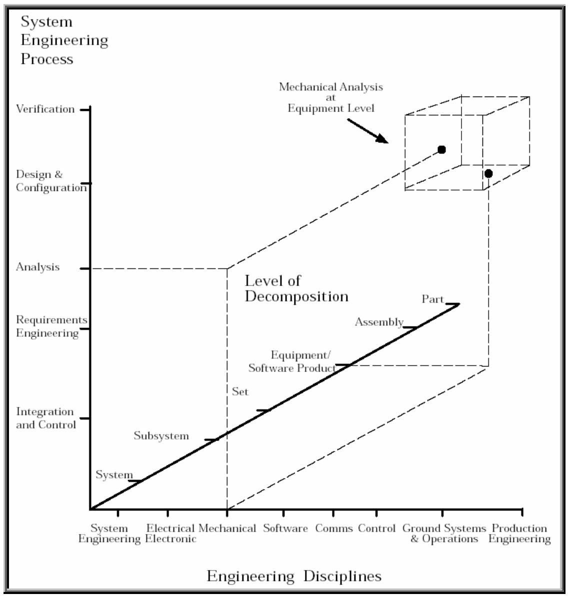

Figure 1. Representation of the engineering domain (Source: ECSS-E-00A. System Engineering. Policy and principles)

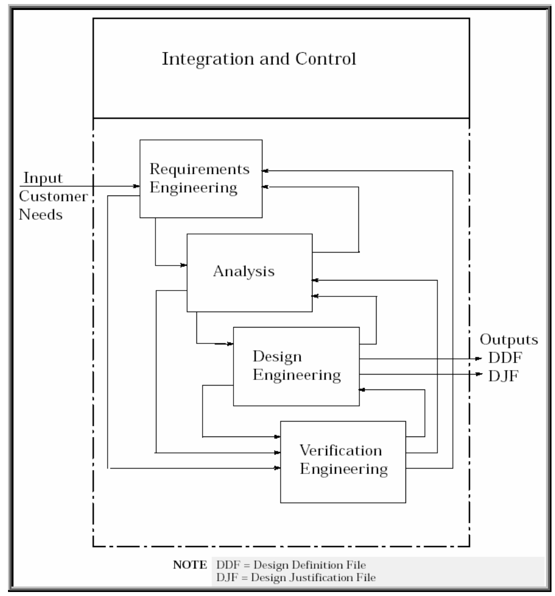

Figure 2. Simplified representation of the system engineering process (Source: ECSS-E-00A. System Engineering. Policy and principles)

On the other hand, the Figure 2 highlights that the essence of engineering process is conceived exactly in the same way that traditional theorists of Engineering Design did [29], [30], [31]. Particularly, the system **engineering process** is implemented through several **functions** that are defined as follows [27]:

- **Requirements engineering** function, which ensures that product requirements are complete, unambiguous and properly express customer's need. It is responsible for the proper interpretation of end–customer needs, coherent and appropriate generation of system and lower assembly level specifications, and day–to–day control of requirement status and traceability. It comprises the following functions: requirement analysis and validation, allocation of requirements to the different components, maintenance and updating of requirements.

- **Analysis** function which comprises two sub functions which although related are rather different in nature: 1) Definition, documentation, modelling and optimisation of a functional representation of the system (functional analysis) and 2) Analytic support to the requirements, design, and verification functions.

- **Design engineering** function which generates a physical architecture for the product, and defines it in a configured set of documentation which forms an input to the production process. In the design and configuration activity, the functional model of the product is defined in a physical architecture (hardware and software). This physical synthesis process, which proceeds from the highest level of complexity to lower levels, is iterated interactively with analysis and verification, to confirm that the required output has been obtained.

- **Verification engineering** function which iteratively compares the outputs from other functions with each other, in order to converge upon satisfactory requirements, functional architecture, and physical configuration, and defines and implements the processes by which the finalised product design is proved to be compliant with its requirements. The most common methods for verification are: test, analysis and simulations, reviews of design, inspections and demonstrations.

- **Integration and control** function which manages the concurrent contributions of all participating functions, of all disciplines, throughout all project phases, in order to optimise the total system definition and implementation. Its main contribution is the planning and management of a fully integrated technical effort which applies the system engineering process at each level of system decomposition during each phase of the project life and controls the achievement at each project milestone through the conduct of technical reviews, risk management, data management, interface management, configuration management and verification.

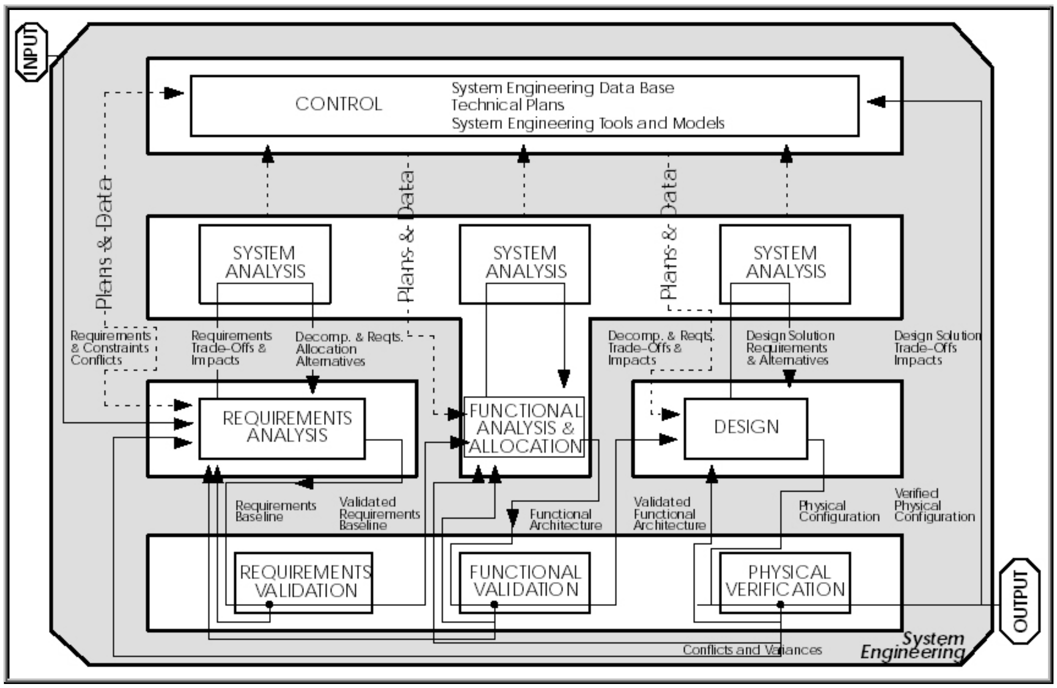

Figure 3. System Engineering Process (Source: ECSS-E-10A. System engineering)

4 Discussion

Taking into account the different types of knowledge and the different cognitive processes, an assessment of the different functions of the engineering process is made. In this way, departuring from the description given at ESA standards [27], [28], we have evaluated which type of knowledge is especially important for each engineering function and which cognitive processes play a special role on it. The discussion is shown in the following tables.

Table 1. Types of knowledge within the engineering process

		TIPES OF KNOWLEDGE			
		A. FACTUAL	**B. CONCEPTUAL**	**C. PROCEDURAL**	**D. METACOGNITIVE**
ENGINEERING PROCESS FUNCTIONS	**REQUIREMENTS ENGINEERING**	Requirements definition is derived from an exhaustive knowledge of the project context, which consists on knowledge about specific facts concerning user demands or other contextual factors.	Knowledge to define requirements includes an interpretation of the context in order to establish the features of the technical system to develop through the engineering process. For this reason, it consists on a deep understanding of the complex relationships which take place in the context of the project.	Procedural knowledge is limited to the use of techniques for requirements management activities such as definition, maintenance, allocation and updating (Ex: QFD techniques).	There is a certain strategic knowledge regarding heuristics to be employed within Requirements Engineering.
	ANALYSIS	Factual knowledge is important for the analysis function, however this knowledge is normally provided by the other functions involved. In any case, knowledge about specific elements and details cannot be discarded as an important component of analysis.	Analysis requires understanding the complex relationships among elements and explaining them through reasons and theories which account for the phenomena which take place. Moreover, modelling is a basic aspect of engineering analysis (Ex: Functional Analysis). Issues concerning assessment and trade of analysis also require a holistic understanding of the different options.	Procedural knowledge is limited to the use of techniques to implement each specific analysis. It is also relevant a certain knowledge concerning the selection of the appropriate technique.	
	DESIGN	Knowledge of specific elements and details is important for design. It is not possible to produce technical solution without a deep understanding of the different elements, configurations, technologies and components involved.	Knowledge of both technological categories their complex relationships within the domain of a certain discipline is a prerequisite for a technical designer. In addition, principles and generalizations, not only scientific or technological ones but also heuristic, are another key issue. In the same way, theories, models and structures are another cognitive referent for the design function.	Procedural knowledge is essential for the design function. Unlike the other functions, design knowledge is action oriented knowledge. Specific skills and predefined algorithms and procedures for the resolution of particular problem are a constant issue in the design function. In the same way, knowledge of specific techniques and methods based on a consensus among the community of engineers is a prerequisite.	Use of heuristics is a metacongnitive component of the design function.

ENGINEERING PROCESS FUNCTIONS	**VERIFICATION**	Knowledge of specific elements and details is basic for the verification function, because this may allow it to check the behaviour of the system in contrast with the established requirements. Knowledge about specific features and behaviours of the system is precisely one of the main goals of verification.	Conceptual knowledge seems to have a less relevant role because verification is not oriented towards the understanding of reasons but towards the certification of fulfilment for a set of requirements.	Verification function strongly depends on procedural knowledge, as long as it involved the implementation of a set of procedures (test, simulation, inspection, revision…) to develop factual knowledge of the system under development. The key for a good verification precisely lies in a proper definition of procedures, with a certain dependence on conceptual knowledge.	
	INTEGRATION AND CONTROL	Factual knowledge in this function refers to elements and details of the rest of the functions.	Conceptual knowledge is focused on the understanding of the engineering domain in itself and the complex relationships which take place during the engineering process.	It is limited to the use of techniques and methods for management and planning of the overall engineering process.	Integration function requires knowledge of strategies for problem solving in the rest of engineering functions. In addition, control function requires specific knowledge about the demands of the rest of the functions in order to manage them.

Table 2. Cognitive process involved in the engineering process

		COGNITIVE PROCESSES					
		1. REMEMBER	**2. UNDERSTAND**	**3. APPLY**	**4. ANALYZE**	**5. EVALUATE**	**6. CREATE**
ENGINEERING PROCESS FUNCTIONS	**REQUIREMENTS ENGINEERING**	*Requirement engineering* depends on the memory of similar projects. The temporary organization which develops the project should encourage both the recognizing and the recalling of events and data.	Understanding of the context is a key issue for definition and updating of requirements. In addition, allocation and maintenance requires understanding of the system under development.	To carry out procedures would be limited to the use of specific techniques for requirements identification and management.			The creative process is focused on the definition of the requirements.
	ANALYSIS	Memory is essential for evaluation. Particularly, recognizing and recalling relevant facts and events is a key issue for the elaboration of a diagnosis.	Understanding is the main goal of the *analysis* function, including each subcategory. Interpreting, classifying, inferring and comparing seem to be in the origin of any technical explanation.	Applying would be limited to the use of specific *analysis* techniques.	To break down the parts of a whole and establish its relative importance is the essence of *analysis*. Likewise, the definition of a structural and functional configuration of the system is one of its main goals.	To evaluate in terms of efficacy, cost, risk and schedule is a specific goal of *analysis*. It is also focused on the detection and resolution of technical contradictions and assessment of the different interacting elements.	
	DESIGN	Recognizing and recalling technical solutions implemented in other context is a necessity for technical *design*.	Specific capability to understand why technical solutions work seems to be important, but not always essential, for *design*. However, cognitive processes such as interpreting, exemplifying, classifying, inferring, comparing and explaining seem to be present during the *design* function.	To a certain limit extent, *design* consists on the application of procedural knowledge that take into account the previous experiences and the consensus reached in the world of engineering.	The arrangement of a physical configuration of the system is a part of the *design* function.		The *design* function is mainly a creative function. Not only technical solutions are defined for each element of the physical configuration, but they are also integrated in a coherent whole. It has a divergent and generative component complemented with a convergent and integrative one.

ENGINEERING PROCESS FUNCTIONS	**VERIFICATION**	Capacity to recognize disagreements between expected and real results is extremely relevant for *verification*. It is also important to recall aspects which can be relevant for the definition and implementation of the procedure.	Comparing would be the main process in relation to the *verification* function. Particularly, comparing the real outputs of the rest of the functions with the expected ones is one of the main tasks of *verification*.	To apply is one of the cognitive processes more relevant for *verification*, as long as it consists on implementing specific procedures to characterize the outputs of the other engineering process functions.		The evaluation process takes place in conjunction with the analysis one in a continuous interaction. However, the *verification* function establishes decision making milestones in the engineering process.	Creation is limited to definition of verification procedures.
	INTEGRATION AND CONTROL	Recognizing and recalling processes are basically referred to different aspects of other functions.	Again, *integration and control* function is oriented towards the understanding of the performance and interactions among oter functions of the engineering process.	*Integrations and control* applies methods and tools to implement its tasks.	*Integration and control* function does not implement analysis processes, but it supports and orientates them on a continuous basis.	*Integration and control* uses evaluation to make decisions concerning the rest of the functions. Particularly, it would guarantee that the function is applied at the adequate level of decomposition.	*Integration and control* participates in the detailed conception of the engineering process itself. It is the through the *integration and control* function that the methodology of the engineering process is defined.

5 Conclusions

The first conclusion we can draw is that each type of knowledge plays a different role within each specific engineering function. In this way, metacognitive knowledge is particularly important in the *integration and control* function, as long as it consist in cognitive processes about other cognitive processes. Analogously, procedural knowledge would be the key knowledge for *verification*, while conceptual knowledge would be especially relevant for *requirement engineering* and *analysis*. The *design* function is perhaps the more complex one as long as it is based both in conceptual and procedural knowledge. Finally factual knowledge seems to be a prerequisite for the implementation of every function of the engineering process.

For this reason, we can assert that there is an intellectual progress through the engineering process which implies an evolution in the types of knowledge involved.

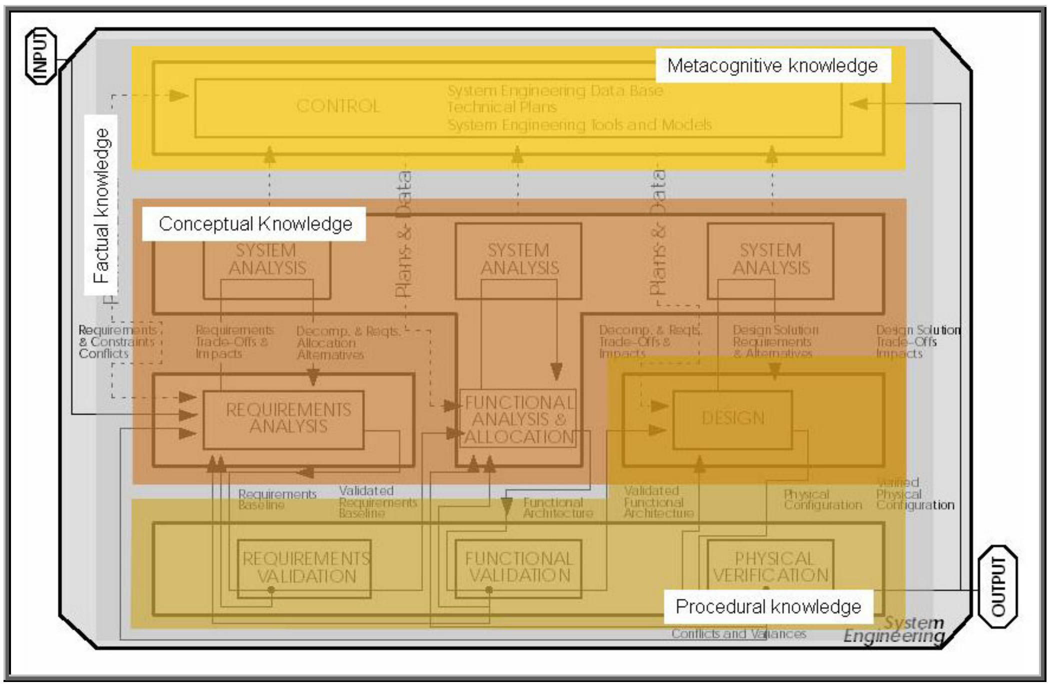

Figure 4. Pre-eminence of each typo of knowledge through the engineering process.

Concerning the cognitive processes, our analysis leads to a new insight into how knowledge is constructed at engineering process. Firstly, understanding processes are linked to *requirements engineering* and *analysis*; secondly, analysis processes have a corresponding function with the same name; thirdly, applying processes are developed through the functions of *verification* and *design*; fourthly, evaluation is distributed through the functions of *analysis*, *verification* and *integration and control*; finally, creation process is developed through the *design* function.

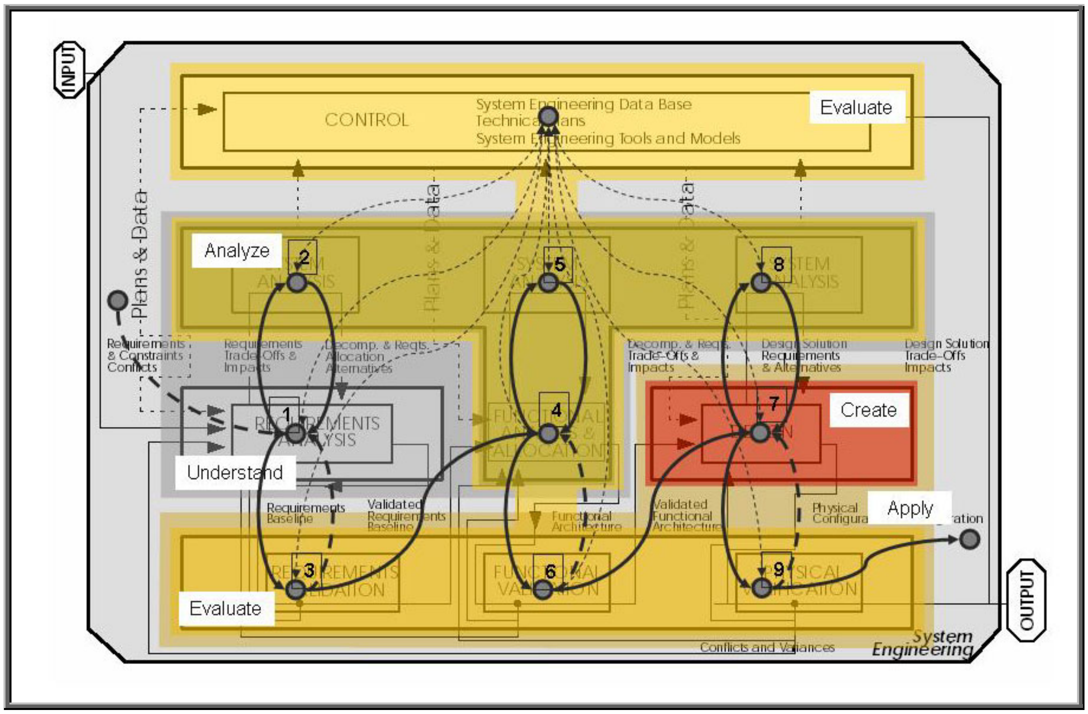

Figure 5. Cognitive processes distribution through the engineering process.

This sequence configures the construction of knowledge through the engineering design process at every decomposition level of the project. In consequence, it can be assumed that it constitutes the learning process which is inherently developed by the temporary organization involved in each single problem of the engineering project.

As far as learning means to develop certain cognitive processes (remember, understand, apply, analyze, evaluate and create) to build several types of specific knowledge (factual, conceptual, procedural and metacognitive), our analysis leads us to assume that engineering process is precisely a complex learning process in which all the cognitive processes and types of knowledge are actively involved.

In conclusion, engineering design would be a learning process which coherently combines all the cognitive processes to create a specific technical solution, that is to say, a new technical knowledge to solve a problem which is specific and original. In addition, we should take into consideration that this complex intellectual process is not individual but collective. For this reason we should consider it as an organizational learning process.

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