DESIGNING CDIO CAPSTONE PROJECTS: A SYSTEMS THINKING APPROACH

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ABSTRACT

Given the all-pervasiveness of Systems thinking -which consists of thinking about things as systems- as a way of reasoning, in this work we will describe its application to make an interpretation of how to conceive and design a final year CDIO capstone course. Both the student teamwork structure as well as the complex engineering system itself addressed in the project are described in terms of entities, links, form and function, thereby pointing out their formal and functional interaction. The ultimate goal of the Systems thinking perspective is, given the necessary ingredients, to try maximizing the chances of the emergence of a fruitful capstone course, namely a culminating project that yields a set of students qualified to CDIO complex engineering systems.

KEYWORDS

Systems thinking, collaborative systems thinking, capstone projects, teamwork, engineering curriculum

INTRODUCTION

Systems Thinking

Systems thinking is the process of solving a complex problem, or a whole, by splitting it into different entities (each of them potentially with a form and a function), the interrelationships between them (again with form and function), the context and its dynamic behavior [1]

Systems thinking is, therefore, a skill that revolves around four basic ideas: complexity, interrelationships, context and emergence: the complexity of a system to solve/operate, the interrelationships between its components, the context at which the system operates and the emergence of the solution/operation.

The term emergence refers to new properties, structures, and behaviors of a higher scale that are not present at the lower scale. Information being quantifiable patterns, emergence can also be viewed as information at a higher scale that is not present at a lower scale; thus, involving information transformation, i.e., computation.

Systems thinking as a vertebral Engineering Skill

The Systems thinking skill enables engineers to solve complex engineering designs and avoid potential problems caused by an insufficient understanding of subsystem interactions or lack of a comprehensive problem exploration. Since engineering is the profession which consists on applying scientific, social, economical and mathematical knowledge to develop solutions for complex problems, systems thinking should be an object of special attention in any engineering curricula. In the engineering context, systems thinking skills include understanding dynamic system behavior, identifying feedback processes, finding and explaining patterns of system behaviour, and identifying ways in which to influence that behaviour [5,7,14].

While engineering education has hitherto provided a solid theoretical and technical knowledge of the different engineering disciplines, the interrelationships between them still have to be emphasized to promote the creative processes and knowledge that emerge from their intersections. This is particularly critical when using analogy to foster creative processes in interdisciplinary fields

Systems thinking in Engineering Education

Several initiatives have been developed to reinforce the links between different engineering disciplines and skills. Amongst them, the Conceive, Design, Implement and Operate educational framework aims to strengthen these interrelationships by allowing the students to apply the fundamental skills of an engineering curriculum to create real-world systems and products.

Placing a team of students in a non-deterministic design environment helps develop communication and decision making skills. Also, exposure to real-world design decisions help teach students to deal with uncertainty [6]

While the interrelationships between the different areas of an engineering curriculum are applied in a CDIO framework, the whole (understood as the complex system of the engineering degree) and the dynamics associated to the different areas/subjects are still unclear. Therefore, this article proposes to use a Systems thinking approach to design CDIO capstone projects in order to 1) apply concepts of different engineering areas (form) on subsystems (functions) which are part of a complex system, 2) strengthen the links (interrelationships) between these areas of knowledge, 3) better understanding of the different areas within an engineering curriculum (context) and 4) emergence of a final design (capstone project).

SYSTEMS THINKING IN A TEAM: COLLABORATIVE SYSTEMS THINKING

A team can be defined as a group of people that has a common task to perform, which differs from a co-acting group only because of the interactions and relationships a team requires between its members [8]. In this sense, a team can be explained as a group of individuals for which a common thinking and knowledge emerges. This emergence is obtained by virtuous interaction between each individual member knowledge, thereby allowing the team to act as a linked net. In a team, the result is greater than the sum of the individual thoughts, enabling a team to deliver more value than a group of individuals.

Why Systems thinking to interpret teamwork?

In order to achieve a task or, similarly, to obtain the emergence of a solution for a complex system, a team must first have a given amount of knowledge. In a team, this knowledge is usually spread amongst the team individuals. Therefore, the team needs to create a virtual web of knowledge by letting its members establish pointers to knowledge held by other team members, thereby creating a transactive memory [7]. These pointers, created through interrelationships between individuals, together with each individual knowledge, conform the transactive memory or knowledge of the team that enables, together with other requirements, the emergence of a final solution.

A team as a System

In a team, each individual has a function (the role such member performs within the team) and a FORM (his expertise profile or the knowledge, skills and capabilities that the member can provide). The sum of his capabilities (C_{in}) and role is what defines his entity (E_i, the individual).

$$E_i = (C_{i1}, C_{i2}, C_{i3}, .., C_{in}) = \sum_{n=0}^{N} C_{in}$$

For EMERGENCE of the task that the team has to perform, the links (L_{ij}) between each individual capabilities and knowledge (to simplify, between each individual) have to be developed, by defining the cross-relationships between each individual entity:

$$\begin{pmatrix} L_1 \\ L_2 \\ .. \\ L_j \end{pmatrix} = \begin{bmatrix} 0 & L_{21} & .. & L_{j1} \\ L_{12} & 0 & ... & L_{j2} \\ .. & .. & .. & .. \\ L_{1j} & J_{2j} & .. & 0 \end{bmatrix}$$

Finally, context awareness (A_{ii}) of the system by each individual needs to be taken into account. Defining context awareness as the sum of awareness of each individual (entity) of the team:

$$A = \begin{bmatrix} A_{11} & 0 & .. & 0 \\ 0 & A_{22} & .. & 0 \\ 0 & 0 & .. & 0 \\ 0 & 0 & 0 & A_{ii} \end{bmatrix}$$

Finally, the figure of merit *FOM* of a team for the emergence/success of its task can be defined as the product of each individual capabilities (C_{in}) by the correlation between team members (L_{ij}) plus the context awareness (A_{ii}) of each individual.

$$FOM = \dot{E}_i \times (A_{ij} + B_{ij}) = \begin{pmatrix} E_1 \\ E_2 \\ .. \\ E_j \end{pmatrix} \begin{bmatrix} A_{11} & L_{21} & .. & L_{j1} \\ L_{12} & A_{22} & ... & L_{j2} \\ .. & .. & .. & .. \\ L_{1j} & J_{2j} & .. & A_{jj} \end{bmatrix}$$

This Systems thinking view of teamwork allows to identify and instantiate that (a) in-depth knowledge and skills of each student alone do not lead to emergence of the final function (b) teamwork alone does not lead to emergence of final function, but that (c) Individual capability, skills and commitment is a necessary but not sufficient condition for emergence of final function of a teamwork targeting a complex system, whereas (d) concurrency of individual capabilities and work together with awareness and interaction with other team members is needed, for which (e) a team leader as project manager for global coherence as well as cross/member awareness is needed

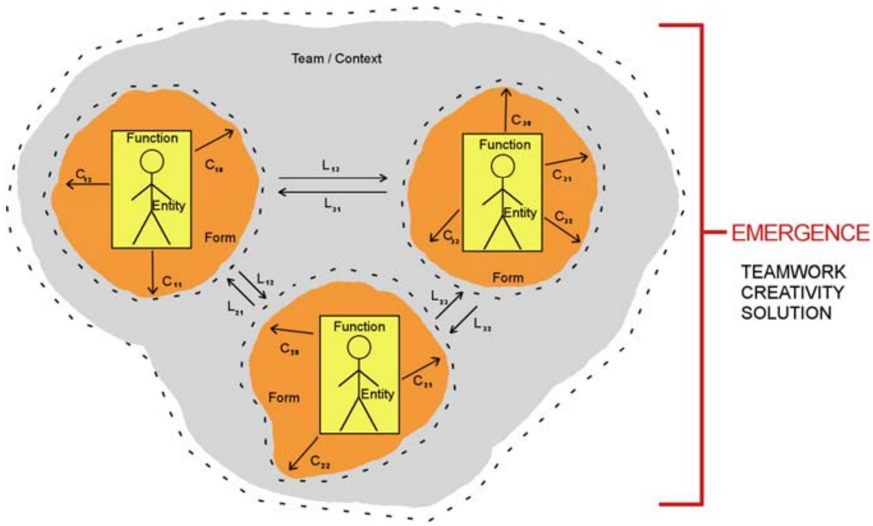

Figure 1. Systems thinking representation of teamwork

SYSTEMS THINKING OF A CAPSTONE PROJECT

A capstone project: a culminating stage to crystallize CDIO skills for complex systems

The engineering or technical outcome of a culminating project is a –complex- system. Hence, it is natural to identify as entities the different subsystems (Mechanical, Communication, Computing, Energy) which have as function the different roles within the system and as form the different capabilities and special requirements of each subsystem. Indeed the entities links correspond to interaction between subsystems. The ultimate outcome of the emergence process is the complete (functional, virtuous) complex system itself.

Why Systems thinking on a Capstone Project:

Capstone projects are considered to be enablers to engineering activity. Engineering requires freedom to explore the design space to make meaningful decisions. A capstone project is hence an adequate context to crystallize CDIO skills while reinforcing core –disciplinary- content. Additionally, a capstone project provides access to resources: both physical resources (lab), monetary resources (project budget) and time (capstone project within engineering curriculum). Beyond the original motivation to address the project objective, the capstone project provides recognition for accomplishments and contributions (capstone project implementation and operation phases). In such a project, tasks and projects provide a sophisticated challenge: this is the pivotal aspect of a Capstone.

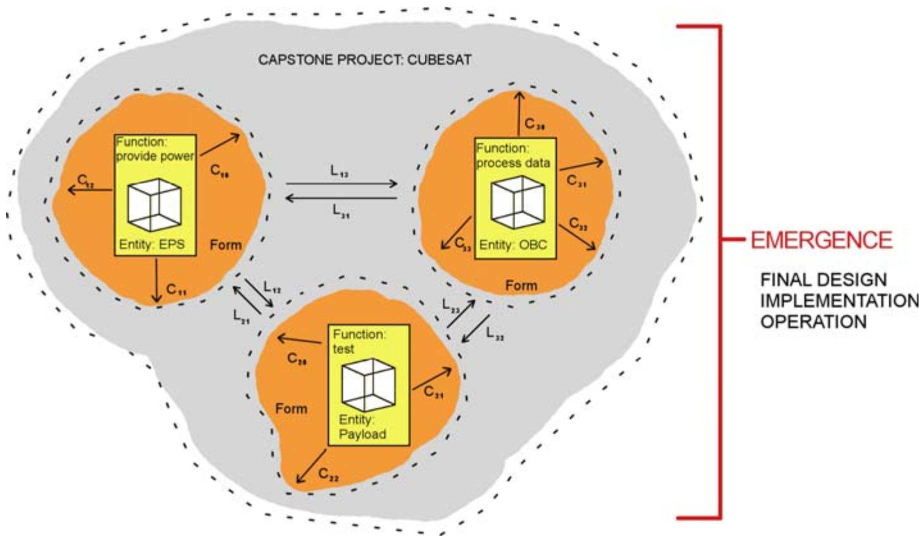

Figure 2. Systems thinking representation of the complex system addressed in a capstone project

This system thinker view of the complex system addressed in the capstone shows that (a) In-depth C,D,I,O of each subsystem alone does not lead to emergence of final function (b) In-depth C,D,I,O of the global system view alone does not lead to emergence of final function (c) Subsystem functionality and system perspective is a necessary but not sufficient condition for emergence of final function of complex system, since (d) functional subsystems and subsystems interaction are key, which is to be achieved by (e) the project technical leader for global technical coherence as well as cross-subsystem awareness.

SYSTEMS THINKING OF AN ENGINEERING CURRICULUM: A META SYSTEMS THINKING APPROACH

The third and final application of systems thinking of a final year capstone discussed in this paper course considers, firstly (after a zoom out), the context in which such project is embedded (the engineering curriculum architecture), and secondly (after a zoom in), a unique initial seminar given prior to the actual design-build experience lab sessions.

As far as the engineering curriculum is concerned, as shown in figure 3, system entities are considered to be the courses, being in turn their function their disciplinary role (and the methodological role of enabling acquiring transversal CDIO competences) within the engineering curriculum, and the form the formal content of the course. Interrelationships between entities composing the curriculum consist of links between courses. Manifestly, the context consists of the group of courses and their impact upon the complete engineering curriculum. The emergence finally consists in learning the engineering discipline for a given output student profile. A common historical drawback of conventional curricula has been the lack of links among course, so that the emergent learning course took much more effort, resource and time (and was only possible for a subset of students) to make that masked link visible and assimilated by the student.

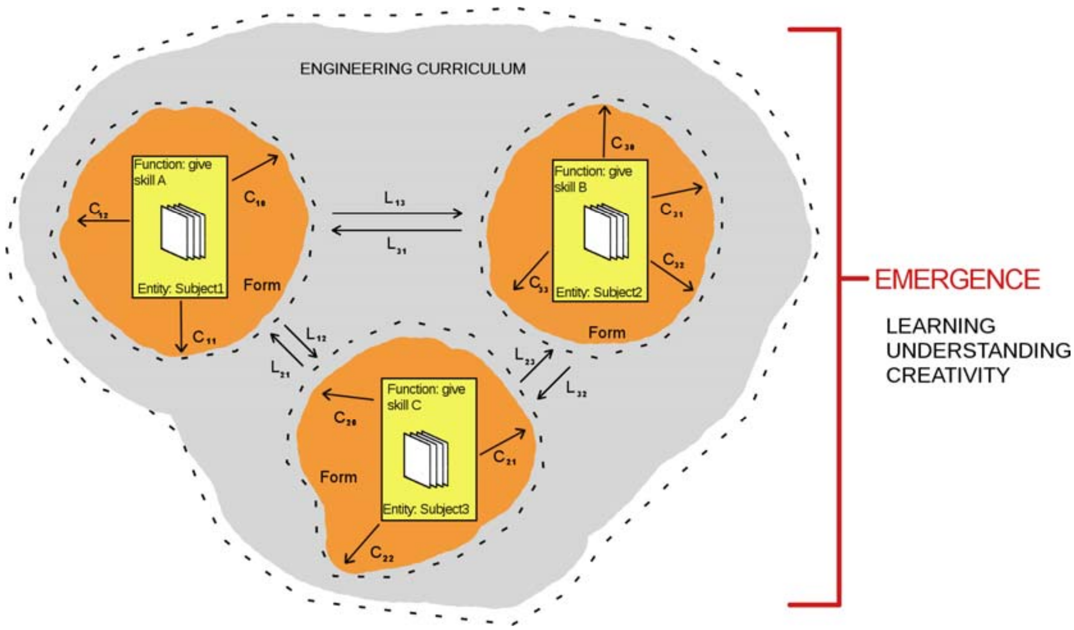

Figure 3. Systems thinking representation of an engineering curriculum

The ultimate objective of this interpretation, and the design guidelines to conceive, design, implement and operate an Engineering Curriculum, is for the student to build to high-level complex systems, namely (1) Engineering (disciplinary) Knowledge (2) the student Engineering Mindset

In our particular environment, the Capstone Design-Build project, intended as a capstone course for students at UPC Telecom BCN, is located in 3rd year. It provides students with a significant design experience and integration of knowledge from several courses in the context of culminating the conception, design and implementation of a complex system. It also provides students with a means to practice Systems thinking, project management, technical writing, and technical presentation skills. Students are expected to gain scientific and/or industrial design experience as much as possible, and students are required to work together in teams and to learn new material.

A crucial aspect of the capstone course is to connect the dots and reinforce contents from regular courses, particularly in their links and interrelationships. With that aim, the structure considered in our School, shown in Fig 4.b, beyond a track devoted to seminars in parallel with the main practical lab of the design-build experience itself, considers as a seminar preamble with a multiple fold objective. This short seminar: (a) first, it introduces the discipline/technological context in which the complex system has to be CDIOed (in our School, a Small Satellite, an acoustics characterization system) (b) a second underlying objective is to revisit in a very short time frame the complete curriculum, projecting, revisiting and reinterpreting course content for the particular complex system application. This revision mainly serves the fundamental purpose of emphasizing the interrelationship amongst courses. It is under this interpretation that this short seminar can be understood as the capstone of the capstone, not only providing and introduction to the project context but also allowing to crystallize the complete curriculum.

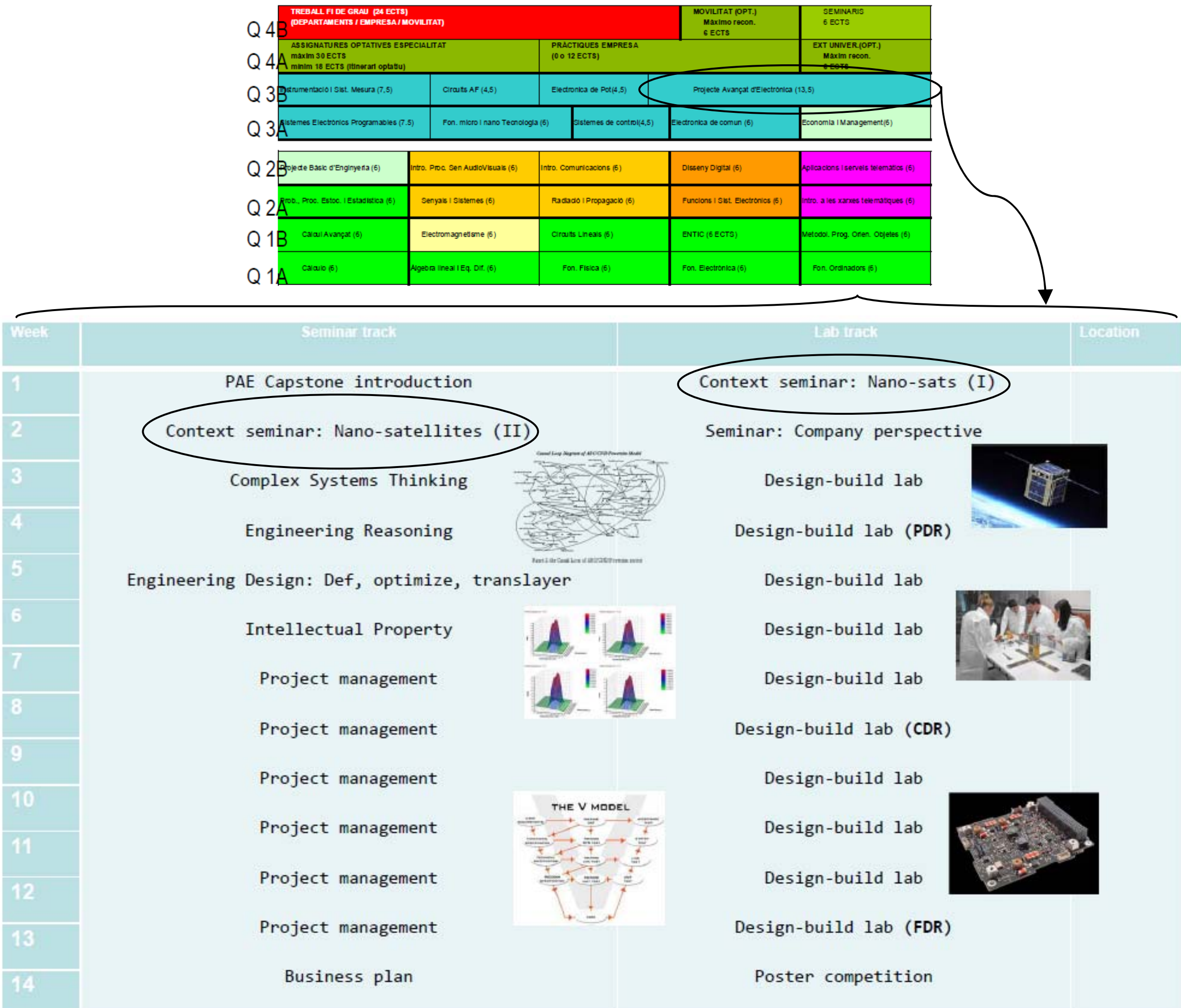

Figure 4. (a) EE Curriculum structure considered at UPC BarcelonaTech, with a 3rd year capstone project [2] (b) Internal structure of the capstone project

CONCLUSIONS

This work has discussed Systems Thinking as a conceptual tool to make interpretations and provide guidelines on how to conceive, design, implement and operate a final year CDIO capstone course. Both the student teamwork structure as well as the complex engineering system itself addressed in the project are described in terms of entities, links, form and function, thereby stressing formal and functional interaction. The different scenarios are represented, formulated and instantiated with the ultimate aim of improving the effect of this culminating courses, both for faculty and students. As a third final outcome, the work discusses a Systems thinking interpretation of both the context and the content of a capstone project, namely of the complete engineering curriculum architecture and of the introductory seminar before the design-build experience aiming to reinforce the whole curriculum content, thereby reinforcing course (and in turn disciplinary and methodological) links. The ultimate goal of the Systems thinking perspective is, given the necessary ingredients, to try maximizing the chances of the emergence of a fruitful capstone course, namely a culminating project that yields a set of students qualified to CDIO complex engineering systems.

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