A Standard Based Adaptive Path to Teach Systems Engineering: 15288 and 29110 Standards Use Cases

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***Abstract*—This paper discusses the use of two different standards for teaching Systems Engineering (SE): ISO/IEC/IEEE 15288 and ISO/IEC 29110. The first one is a general and widely-used standard describing the lifecycle processes of the entire system, whereas the second one is a relatively new standard based on a reduced set of standards elements focused on lifecycle profiles for Very Small Entities (VSEs). We are especially interested in the impact that SE standards can have on teaching this discipline to engineering students. We consider the teaching of fundamental principles of systems engineering. In this paper we illustrate how our, previously developed, standard based solution for systems engineering education can be used as a framework to support these standard-based teaching paths. We mainly focus on illustrating how adapting standard processes can be done, considering not only the learning goals, but also projects size and complexity, in a project-based learning environment.**

This paper shows that, thanks to it's adaptation from the ISO/IEC/IEEE 15288, and to it's reduced size, the ISO/IEC 29110 standard is particularly suitable for teaching systems engineering fundamental knowledge to undergraduate students, new to the discipline. While the ISO IEC/IEEE 15288 might be more suited for students that already have a good grounding in systems engineering fundamentals, especially thanks to the ability to use some from its various processes to separately teach different topics of systems engineering.

Keywords: Systems Engineering , Systems Engineering Education, Systems Engineering Standards, Project-Based Learning, ISO/IEC/IEEE 15288 Standard, ISO/IEC 29110 Standard, Life Cycle Model.

I. Introduction

Systems Engineering (SE) is a structured approach focusing on the design and the management of complex engineering projects over their entire life cycle. It is presented by the International Council on Systems Engineering (INCOSE), as *"an interdisciplinary approach and means to enable the realization of successful systems. It focuses, not only on defining customer needs and required functions early in the development cycle, but also, documenting requirements, proceeding with design synthesis and system validation, and considering the complete problem are in the scope of Systems Engineering"* [1]. This discipline has known much efforts trying to promote its adoption by different industries, especially when the complexity of nowadays systems has increased to an unprecedented level. This complexity is caused at the first place, by the multidisciplinary aspects of modern systems along with, their multiple involved stakeholders, and their geo-located engineering context. These efforts are primarily, development of multiple international standards, guides and methodologies, to help the industry adopting this approach [2]. However, many academic institutions have not coped with systems engineering challenges, and have not sufficiently considered its specifications and requirements when implementing their engineering curriculum. So, while the engineering industries may better cope with the complexity problems, thanks to the different efforts done in this domain, they face a significant lack of well-trained human resources who master the fundamental and domain-specific systems engineering principles and their corresponding standard processes. Standards and their related processes and methods are one of the most sought after skills, but academic institution, as stated in our review study [3], have not kept up with this demand. From an industry perspective, in order to be effective as systems engineers, in addition to the necessary knowledge in their traditional engineering disciplines, engineering students need practical and real world experiences, acquired in reality-like geo-distributed and multidisciplinary context. It needs to be a skills focusing and challenging context[4], more than being a knowledge focusing one, what presents real challenges from academic perspective. To cope with these challenges, we proposed in [5] a new technology-based solution to teach systems engineering.

Our proposed solution, presented in section (IV), enables educators to work on an adaptive path for teaching this discipline, by giving them the ability to adapt their learning scenarios. Educators are able to select and adapt standard processes to make them more suited for each learning situation. We illustrate two use cases using the 15288 and the 29110 standards in section (V) of this paper. In section (II) and (III) we respectively, highlight the specifications and requirements of systems engineering education and the leading standards in this discipline, with a focus on the previously cited ones.

II. Systems Engineering Education

According to Muller [6], systems engineering education differs from traditional mono-disciplinary engineering courses, since the training needs to focus more on skills and less on transferable facts. The author gave a set of recommendations to consider for a good systems engineering education program, including interaction with students, soft skills development, media use and students feedback. In the same context, Dym [7] believes that "*a good engineering education is about process, about learning how to think like an engineer; its much more than a prescription of content*".

Dym et al. [8] recommend the following three activities for a powerful learning environment for systems engineering and similar disciplines:

- *Instrumenting the learning process to obtain quantitative and qualitative data that support metrics consistent with quality control.*
- *Teaching design engineering and other disciplines such as systems engineering across geographically dispersed, culturally diverse, international networks*
- *Engage design coaches to help manage the contextualization of engineering design theory and practice.*

Finally, in a broader context, Herrington and Kervin [9] specify nine main characteristics that any learning environment, technology-based or not, should feature:

- *Provide authentic context that reflects the way the knowledge will be used in real life*
- *Provide authentic activities*
- *Provide access to expert performances and the modeling of processes*
- *Provide multiple roles and perspectives*
- *Support collaborative construction of knowledge*
- *Promote reflection to enable abstractions to be formed*
- *Promote articulation to enable tacit knowledge to be made explicit*
- *Provide coaching by the teacher at critical times, and scaffolding and fading of teacher support*
- *Provide for authentic, integrated assessment of learning within the tasks*

It appears clearly, from the work we presented in [3], that most of systems engineering current practices don't take these considerations and recommendations into account when designing their curriculum, and none of them considered the use of SE standards during the learning scenario. However, this survey [3] helped us defining the perimeter and the features of our solution, that will be presented later. This helps us especially deciding to focus our efforts in incorporating systems engineering standards in the learning scenarios, and to select the Project-Based Learning (PBL) as a pedagogical model.

III. Systems Engineering Leading Standards

A. SE Standards Overview

Systems engineering addresses the complexity of systems, in order to be able to transfer user needs into operational systems via an interdisciplinary processes. The early standard for systems engineering was the US Military Standard MIL-STD-499, Engineering management from 1969 [2], produced by the US Department of Defense (DoD) for the defense industry. It has been adapted twice after that, the MIL-STD-499A release on May 1st , 1974, and the MIL-STD-499B draft on 1992. By 1994, a group of organizations called Electronic Industries Alliance (EIA) collaborate to develop a commercial systems engineering standard to replace the military one. This group included representatives from the DoD, the Aircraft Industry Association (AIA), the National Security Industries Association (NDIA), the Institute of Electrical and Electronics Engineers (IEEE), and INCOSE [2]. By December 1994, they released the EIA Interim Standard 632 (EIA/IS 632) Systems Engineering. This Standard became later the ANSI/EIA 632-1998, Processes for Engineering a System [10], which has been approved on January 7th, 1999.

The IEEE , the International Organization for Standardization (ISO) along with the International Electrotechnical Commission (IEC), have also worked on developing systems engineering standards. By 1998, and after a trial-use version by 1995 (IEEE Std 1220-1994) [11], IEEE produced the IEEE Std 1220-1998, standard for application and management of the systems engineering process [12], and by 2002, ISO and IEC released the ISO/IEC 15288 standard, systems engineering-system life-cycle processes [13], which has been created by the same group that created the ISO/IEC 12207 software life-cycle standard, in collaboration with systems engineering experts [2].

Each of these three different Commercial standards, EIA 632, IEEE 1220 and the ISO/IEC 15288 addressed various level in the systems engineering processes. While the last active version of the EIA 632, processes for engineering a system, still the one approved on 1999 and reaffirmed on 2003, and the IEEE 1220 that has been revised once on 2005, which still be the actual active version of this standard [14], the ISO/IEC 15288-2002 after its adoption by IEEE in 2004, has been revised by the ISO/IEC 15288:2008 [15], before it has been canceled and replaced by its final revision, the ISO/IEC/IEEE 15288:2015 [16] which was prepared by Joint Technical Committee ISO/IEC JTC 1 (Information technology), Subcommittee SC 7 Software and systems Engineering), in cooperation with the IEEE computer society systems and software engineering standards committee [Ref152882015standard]. In 2004, ISO/IEC 15288-2002 has been adopted by IEEE, in the IEEE Std 15288-2004 [17], Also, INCOSE adopted this standard and aligns upon it, the process and life cycle content in their 4th Version of the SE Handbook [18]. ISO/IEC/IEEE 15288, by gathering all the important normalization institutions and big industrial around it, is becoming the most revised and the most complete standard for systems engineering. It's becoming the starting point of many derivative products, different institutions and researchers, in order to support it, are producing content, guidance, reports, use cases...etc. Others are creating completely new products, such as the ISO/IEC 29110 standard [19] , which is a Systems and Software Life Cycle Profiles and Guidelines for Very Small Entities (VSEs). ISO/IEC 29110 is mainly based on ISO/IEC/IEEE 15288 for systems engineering part, and on the ISO/IEC/IEEE 12207 for software engineering part. This was just a sample set of standards, to show their importance in the field of systems engineering, for more information about systems engineering standards, especially in some specific disciplines, you can take a look at Incose website [20]

B. Illustrative Standards

Based on the previous overview of the different systems engineering processes standards, and as our goal is to illustrate our adaptive learning path, we consider the use of ISO/IEC/IEEE 15288 and ISO/IEC 29110 as the best choice. Especially because one of these standards covers the entire life cycle of a system, with a large number of different individual processes, while the other one, is a smaller set of processes focusing on the need of VSEs, some of their advantages are listed here.

*1) **The ISO/IEC/IEEE 15288 Standard**:* The most significant characteristics of the ISO/IEC/IEEE 15288 are:

- It is the systems engineering reference standard, and it is promoted by mainly all the standardization organizations including IEEE and INCOSE. It is up-to-date and based on proven practices.
- Our aim is to let the students learn the fundamentals of systems engineering, but we don't want to bother them with high level of details relative to deeper processes application. However we want educators to be able to select most suited topics to learn for specific students, and for which kind of systems. This standard provides them with the ability to do that.
- Its processes can be applied in different manners: concurrently, iteratively and recursively to a system, and incrementally to its elements. It can be applied to a an element of a system, considered as a system itself, as it can be applied at any level in the hierarchy of a system across its life cycle.
- It applies to man-made systems configured with one or more of the following, hardware, software, humans, or processes.
- When defining the life cycle model and its different stages, educators can choose which of this standard processes to consider in order to be in conformance with. But also, its processes can be tailored to fit a specific learning goal for example.
- It can be used alone or jointly with the ISO/IEC/IEEE 12207, for software engineering, which has the same terminology and concepts.

In its last revision of 2015, it includes 30 processes grouped into four categories.

- Agreement processes: 2 processes
- Organizational Project-Enabling Processes: 6 processes
- Technical management processes: 8 processes
- Technical processes: 14 processes

For each process, this standard provides us by:

- Its Purpose: a paragraph that describes at a high level overall goal of performing the process.
- Its Outcomes: Outcomes express the observable results expected from the successful execution of the process.
- Its Activities : Activities provide the first level of structural decomposition of a process, they generally provide a set of the related lower-level elements called Tasks.
- Its activities tasks: Tasks are requirements, recommendations, or permissible actions intended to support the achievement of the outcomes.
- and some Notes:

This standard provides a common processes framework for describing the life cycle of systems created by humans, adopting a systems engineering approach[16]. It does not describe a specific system life cycle model, neither a development methodology, method, model or technique.

*2) **The ISO/IEC 29110 Standard**:* The most significant characteristics/advantages of this standard and its differentiation regarding the first one are:

- The recently published set of ISO/IEC 29110 international standards (IS) and Technical Reports (TR) [21] are specifically aimed at addressing the specific needs of VSEs (Very Small Entities), i.e., enterprises, organizations, departments or projects with up to 25 people.
- The engineering standards and guides developed by an ISO working group, Working Group 24 (WG24), are targeting VSEs which do not have experience or expertise in selecting, for a specific project, the appropriate processes from life cycle standards such as ISO/IEC/IEEE 12207 or ISO/IEC/IEEE 15288, and tailor them to the needs of a specific project [22].
- Building upon the success of ISO/IEC 29110 for software, in 2009, an INCOSE working group was established to evaluate the possibility of developing a standard using the generic profile group scheme of the ISO/IEC 29110 series and the systems engineering life cycle processes standard ISO/IEC/IEEE 15288 (2008), for organizations developing systems instead of just softwares. This new ISO/IEC 29110 standard is targeted for VSEs that do not have experience or expertise in tailoring ISO/IEC/IEEE 15288 to their needs. The result is the publication of a Systems Management and Engineering Guide Entry profile (ISO/IEC TR 29110-6-5-1:2015), i.e. for VSEs working on small projects (e.g. at most six person-months effort) and for start-up VSEs and Basic Profile (ISO/IEC TR 29110-6-5-2:2014) [23].
- The systems engineering basic profile is composed of two processes: Project Management (PM) and System Definition and Realization (SR). An acquirer provides a Statement of Work (SoW) as an input to the PM process and receives a product as a result of SR process execution, see Figure 1.

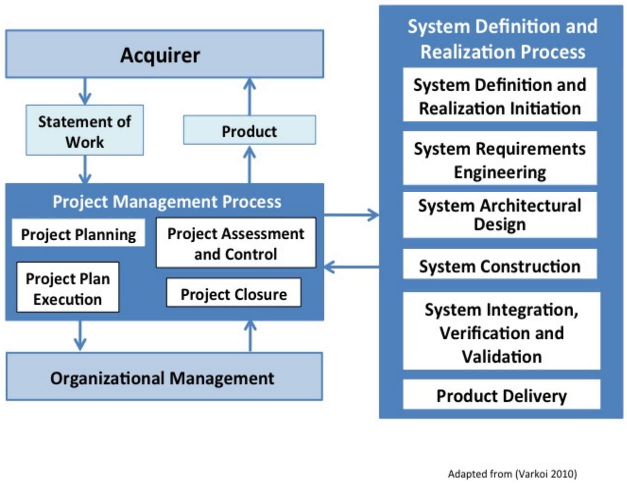

Fig. 1. ISO/IEC 29110-6-5-2:2014 architecture

IV. Solution Description

In this section we describe our solution and highlight its main features, more details about the full solution can be found in [5]. At this stage, the developed solution only allows us to work with one kind of processes: the technical processes. These processes allow users, students in this case, to engineer their systems, without dealing with other kinds of processes, such as the management, agreement, and project-enabling processes.

One of our main goals is to help systems engineering education organizations improve their SE teaching experience, and as stated before, we are focusing on the teaching of the fundamental principles of systems engineering. This fundamental knowledge, when correctly acquired by students allows them to easily adapt it to meet the specific industries needs in terms of systems engineering skills. For this main reason, we decided not to build this solution upon an existing systems engineering methodologies, which may limit us by imposing some kind of tools, methods, or processes to follow even if they are not fully adapted to the system-of-interest being engineered by students, or simply not fulfilling the learning experience requirements. Rather, our solution is process-centered, hopefully standards ones, while still being independent of the specific standard choice. It provides the learner and educator with the ability to work on the different stages of a life cycle model using any systems engineering standard processes. We illustrate in the next section, two different use cases using two different standards.

From the adopted systems engineering standard, the educator can easily register in the solution the different processes he's interested in, while personalizing them or not. See Figure 2 bellow, for an example of a process registered in the solution. Then, for each new project regarding the engineering or re-engineering of a system, educators are able, through a specific interface, created for that effect, to define the project life cycle model and share it with students. They can choose to make students passing through all the proposed processes in the standard, or just through few of them, and also adapt standard processes depending on what type of conformance with the standard they want to claim for their system-of-interest, but also depending on the project characteristics and the learning goals.

The defined life cycle model, will be then followed by students to engineer the requested system, by performing the different activities and tasks. They will be working on a collaborative project based approach, using the recommended tools, methods, and resources, while producing the expected outputs. An example of students workspace, including the system life cycle at the left, is illustrated in Figure 3 below.

In order to illustrate how different standards, with different adaptations can and should be implemented in this solution for teaching purposes, we only need to use the following three features from our solution:

- **Processes Management System:** allows educators, to register systems engineering processes in the solution. Educators are able to create new processes, or adapt existing ones.
- **Life Cycle Management System:** Here, the Life cycle model is defined by the educator, using the systems engineering processes, defined inside the processes management system.
- **Students Engineering Workspace:** This represents the workspace where students work in collaboration mode to engineer the requested system. In short words, it allows students teams as producer of the system-of-interest,to follow the project life cycle model, in order engineer the system. They can, depending on the role of each one, start performing their tasks and activities to get the expected outcomes, and reporting them in the adequate process element in the solution menu, so, everyone from the group, including the educator, can be aware of the progress in the project. This help them, very early detecting if there is a system requirement definition gap, a misconception, a validation problem, or any other problem, and report it.

V. Illustrations

- **Case No.01:** Introduction to requirements engineering using the 15288 Standard
  Learning Goal: The goal of this use case is to make students learn the different aspects of the needs and requirements engineering, through the realization of a project proposed by the educator. Figure 4, show the definition of the project "*Requirements for a 3D Racing-Car Design Project*". This will enable them to go from defining the problem and solution spaces, until defining the technical view of the solution that meets operational needs of the user, passing through stakeholder identification with their needs. In shorter words, they should pass through the defined system life-cycle model illustrated in Figure 3 and 4.

Fig. 2. 15288 stakeholder needs and requirements definition process, implemented in our solution

Used processes: Using the 15288 standard, students needs to pass at least through three processes: the *Business or mission Analysis Process*, the *Stakeholder Needs and Requirements Definition Process* and the *System Requirements Definition Process*, as shown in Figure 3, that represent students workspace containing the three processes forming the system life-cycle model.

Note that, this is just an illustration use case, we can do the same thing about learning the system design, system verification, validation, and other topics of systems engineering using the 15288 standard processes. The main significant thing that must be considered at this cases, is that educators, need not to only define the project and life cycle, but also to provide the necessary inputs, such as the systems requirements. educators can even make students pass through the entire life cycle technical processes of the 15288 or another standard. Next, we'll show how this can happens using the 29110 standard this time.

- **Case No.02:** Introduction to SE through the entire technical system life cycle model, using 29110 standard
  Learning Goal: This time, we are interested in teaching more aspects of systems engineering, those conveyed by all the technical processes of the entire system life cycle processes. We also aim to teach students these aspects using a PBL approach, using the previously defined project, with some adaptations, like the fact that, this time students have to fully engineer the requested Racing-Car, going from system definition to systems delivery.

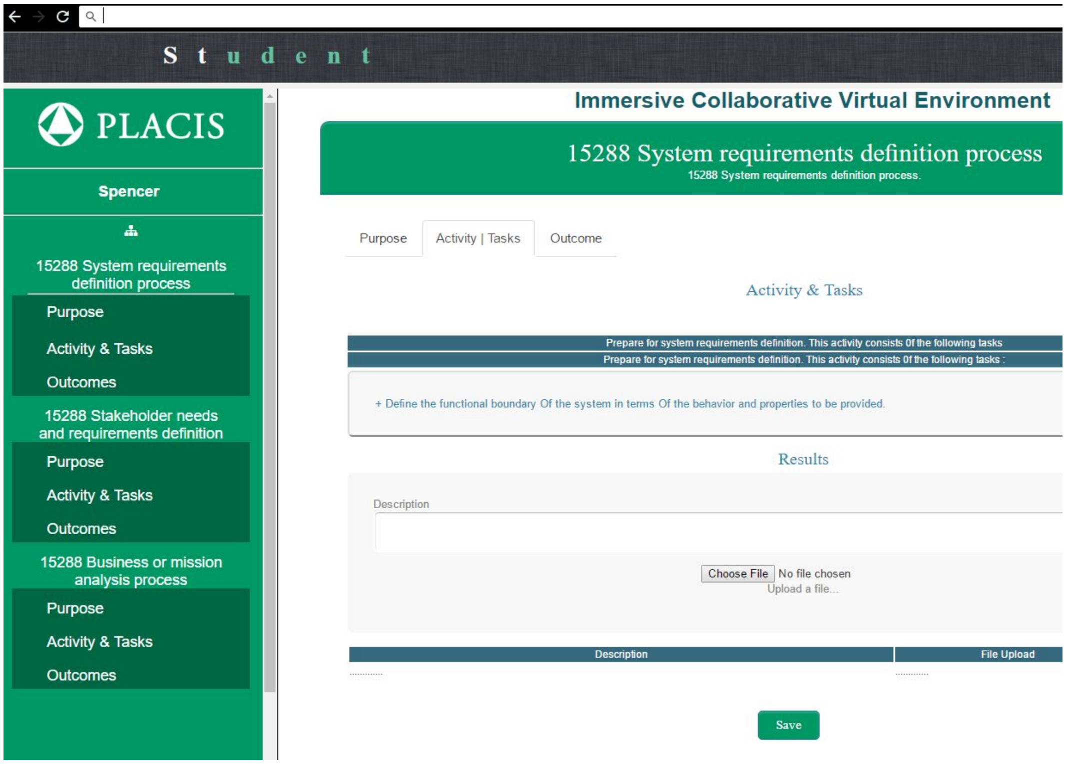

Fig. 3. A example of students workspace, showing the system-of-interest life cycle model at the left, and the different tasks and activities execution space, for a specific process "15288 System requirements definition process"

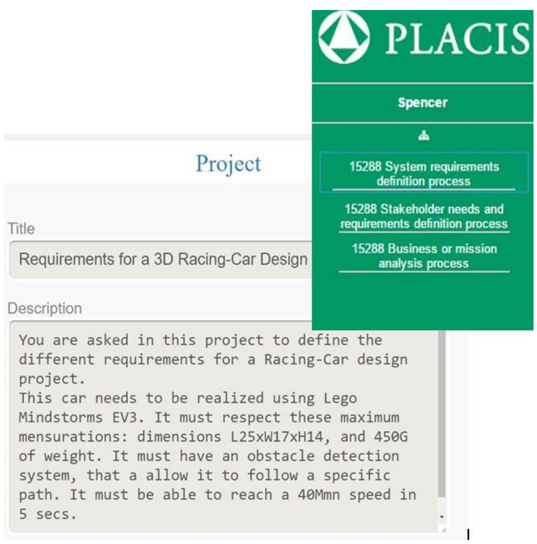

Fig. 4. Project description and related system life cycle model

Used Processes:

This time, we think that using the 29110 standard will be more appropriate, especially for small teams of students, dealing with simple pedagogical systems, and who are new in systems engineering. The educator defines the system life cycle model inside this solution, according to the 29110. More specifically, the system life cycle model is defined based on the generic profile group: Entry profile, from systems engineering management and engineering guide ISO/IEC TR 29110-5-6-1 [24]. It was intended to be used by VSEs to establish processes to be implemented using any development approach or methodology, based on the specific VSE or project needs. What we consider as technical processes, are defined in this guide, as a single process called *System Definition and Realization (SR) process*, see Figure 1. This global process has six activities: SR.1 System Definition and Realization Initiation, SR.2 System Requirements Engineering, SR.3 System Architectural Design, SR.4 System Construction, SR.5 System Integration, Verification and Validation, SR.6 Product Delivery [24]. These activities can be considered at the same level as the 15288 technical processes.

Since the technical processes are considered as activities forming one global process, the SR Process, they will be implemented such as in the platform. So, the system life cycle model in this case, even if it represent the entire technical life cycle model, consists of only the SR Process. This process is defined in the platform by it's name, purpose, and its Seven objectives as outcomes. Then, the different activities, representing each, the equivalent of a technical process in the 15288, are added as activities, and their related tasks as tasks. At this level of maturity of our solution, we don't take the *Roles* described in

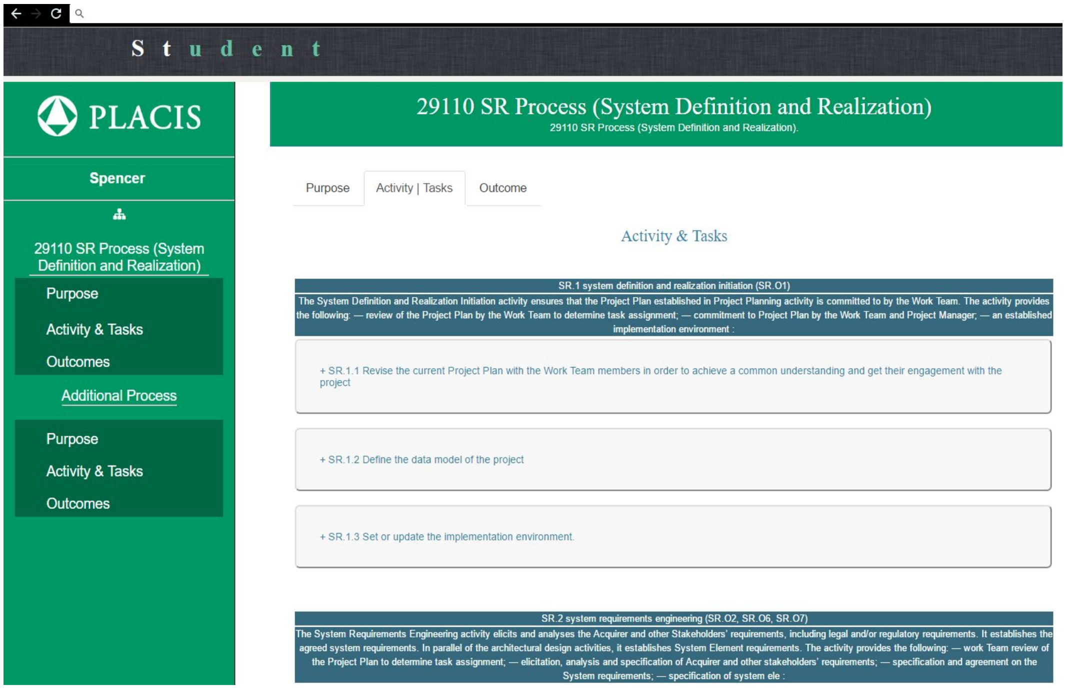

Fig. 5. A example of students workspace, showing the system-of-interest life cycle model at the left, and the different tasks and activities execution space, for a specific process ”29110 System definition and realization process”

this guide into consideration. *Input Products* and *Output Products* can be considered as the results students will be uploading in each task space, even if their links with other activities are not managed in the actual solution. At the end, students will have the workspace illustrated in Figure 5.

VI. Conclusion and Further Work

Systems engineering international standards, encompass from one side the fundamental knowledge of systems engineering, and from the other side, they have been used as the main source of competencies used in different systems engineering competency models, including, the Incose, Nasa, and other competency models. We showed in this paper, how systems engineering teaching and learning will be improved by adopting these standards when developing our solution. The greatest impact is especially remarkable regarding the learning outcomes compared to the systems engineering competencies, described in different competency models. The most significant advantage of the proposed solution reside in the fact that educators, starting from which competencies they want students to learn, they are able to tailor different systems engineering standards and their processes to teach them students. In addition, the ability of this solution to get students working together using a technological solution in a PBL-Based approach from different locations, to engineer the same system, by passing through the entire life cycle model defined by the educator, enables students to learn the other part of systems engineering competencies, including the soft skills, the team management, ...etc, which needs to be learned by practice. We highlighted in this paper the ability of this solution to be used with different standards, using different adaptations, depending on the project type and learning goals.

We are still working on improving this solution, by enhancing its outcomes for both students and educators. We are working on a new way to evaluate students, and improving by the way PBL assessment challenges. We are doing that by sharing with educators a vision of all what is happening during the project engineering time, but also by putting some KIs (Key Indicators) in the students work-space, and sending the extracted information to the educators. This will enhance students evaluation regarding: their results, execution quality, along with their acquired Knowledge and Skills, and enable educators to set which systems engineering competencies are learned and what still need to be learned, for each student.

We can go further in the possibilities of adapting the learning path, so it can fit systems engineering wanted skills, such as the communication and time/cost management. We can, for instance imagine a new learning path where different independent groups of students are working on the same project. In this case, group A is responsible of the needs and requirements engineering, group B on the system design and architecture, group C deals with system construction and finally group D with system integration, verification, and validation. At this case, the repartition of students among the different groups should be done based on their systems engineering competencies, and the competencies they had to learn. However, in order to make this really happening, some additional features are needed in this solutions, such as adding new communication channels, to enable teams to communicates together, and making it possible to use standardized management and agreement processes in the solution, in addition to the technical processes. We can also ensure that, in some situations, students will define and manage their system life cycle model by themselves. This can make students get a larger picture of what systems engineering is about, and making them able to speak the systems engineering language, at different levels.

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