AN INNOVATIVE APPROACH TO INTERDISCIPLINARY EDUCATION THROUGH DOMAIN SECTOR COURSES

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ABSTRACT

This paper outlines a framework for interdisciplinary education through domain Sector Courses. The respective set of industrial Sector Courses is conducted at the Skolkovo Institute of Science and Technology (Skoltech). The proposed framework is based on a holistic approach to an industrial sector, considering it with multiple lenses, including technology, business and policy, which provide an interdisciplinary content fundamental to the teaching of innovation. The core idea of a Sector Course is to build a holistic knowledge about a given economic sector and its main actors. In this paper we discuss three examples of the courses offered at Skoltech: a Space Sector Course (Menshenin et al., 2020), a Power Markets Course and a Product Development and Manufacturing Course. All of these courses are called "Sector Courses" taught for graduate-level students and are built upon the CDIO framework (Crawley et al., 2014; Crawley et al., 2013), integrating its standards to support students' knowledge and skills. We discuss the general approach to building the Syllabus and learning environment in these courses and how these are realized through the CDIO framework. We also describe what elements of the courses are essential and how – when combined together – they lead to the specific set of learning outcomes of such courses. The practical utility of the proposed paper is that it outlines the core principles of the economic sector courses based on the CDIO approach. Such principles allow the systems educators to build a Sector Course in any domain of interest, facilitating the students' knowledge and skills development to foster innovation.

KEYWORDS

Innovation, entrepreneurship, interdisciplinary thinking, systems thinking, critical thinking, Standards: 1, 2, 7, 8

INTRODUCTION

This paper outlines the framework for interdisciplinary engineering education through the domain Sector Courses. Such courses are aimed to cover a specific industrial sector by providing a holistic view of it from a variety of the engineering and business viewpoints. We base our discussion on three Sector Courses offered at the Skolkovo Institute of Science and Technology (Skoltech): the Space Sector Course (SSC) (Menshenin *et al.*, 2020), the Power Markets Course, and the Product Development and Manufacturing Course. These are regular university courses taught for graduate-level students and built upon the CDIO framework (Crawley et al., 2014; Crawley et al., 2013), integrating its standards to support students' knowledge and skills acquisition. These courses are M.Sc. and PhD levels courses worth 6

ECTS and taught at Skoltech in the English language. The Space Sector Course that is considered in this paper in detail is a compulsory course for the students in the Space and Engineering Program, which is one of the official programs for graduate level students at Skoltech.

The objective of our paper is to present a general framework for the Sector Courses in any domain of interest. Such a framework aims to specify what are the core elements of the course and how – when combined together – these elements lead to specific learning outcomes for this type of course. We discuss one of the courses, the Space Sector Course, in detail as a case study. The practical utility of our paper is that it outlines the core principles of the Sector Courses based on the CDIO approach. We also present the architecture of one the courses using the Cloud-based OPCloud modeling environment (Dori et al., 2019), which provides a good synthetic view of the components and architecture of the course.

Sector Course Definition

A “Sector Course” is designed to provide a holistic content of an industrial sector, considering it with multiple lenses, including technology, business and policy, which provide an interdisciplinary perspective, fundamental to the learning of innovation. The core idea of a Sector Course is thus for the students to develop a more holistic knowledge about a given economic sector: its actors, its priorities, its technological, economic and societal challenges, its history.

“Holistic” Approach to Engineering and Business

The emphasis of such a course is thus placed on the breath of the content by inviting various actors to present their specific point of view and by giving the students an opportunity to reflect on the integration of these various points of view. Critical thinking can play a vital role in such a course because it provides useful tools for the students to study the various points of view presented from a number of media sources. This allows them to deepen their understanding of the given economic sector and open their mindset to how they could possibly become proactive actors in this domain.

Innovation and entrepreneurship have become an important learning outcome in the extended CDIO Syllabus 2.0 (Crawley et al., 2011) and also in some of the highly recognized engineering programs such as MIT, SUTD, UCL and Chalmers as reported by Graham (2018). To implement these advanced learning outcomes concrete content and learning experiences must be integrated into the curriculum to reach these goals. The approach of the Industrial Sector Courses is such a concrete mean to implement the innovation and entrepreneurship in a curriculum.

Skolkovo Institute of Science and Technology (Skoltech)

Skoltech is a Moscow-based university that was founded in 2011 in collaboration with MIT. It offers the graduate programs in a variety of disciplines – from space and energy to biomedicine and IT. From the very beginning of its existence, Skoltech has been actively developing its courses following the CDIO approach (Crawley et al., 2014).

Skoltech is broadly recruiting the graduate-level students from different disciplines related to science and engineering. Skoltech is primarily focusing on searching for students who have a solid fundamental background and are motivated to bring together science and technology &

entrepreneurship and innovation. All students are receiving scholarships and are studying in the English language.

In our paper we discuss the key aspects and takeaways of the application of the CDIO principles to Sector Courses at Skoltech.

OVERVIEW OF SECTOR COURSES

Our paper is based on the experience with running three courses offered at Skoltech: The Space Sector Course (SSC) (around 120 students completed the course since 2014), the Power Markets Course (around 70 students completed the course since 2014) and the Product Development and Manufacturing Course (around 25 students completed the course in 2015). The detailed courses descriptions are outlined in Table 1.

In our paper we discuss in detail the SSC as a Case Study in the next section, yet we argue that the principles of the Sector Courses remain the same regardless of the field. Thus, the proposed approach could certainly be used for other sectors of engineering education.

Table 1. Sector Courses Descriptions

Course Name	Course Description
Space Sector Course (SSC)	This course examines the domain of space from multiple vantage points — space as a business, a way of life, a fulfillment of human dreams. In addition, it examines space-related issues that drive key international regulatory, economic, and global policy. To gain insight into these different dimensions, we examine space through three different lenses: sub-sectors, technologies, and organizations.
Power Markets Course	The course will introduce the students to power system economics. After covering the fundamentals of microeconomics, the main types of electricity markets and regulations will be discussed including the Russian market. Economic dispatch and Optimal Power Flow with Locational Marginal Pricing will be covered. Capacity planning, ancillary services, and risk analysis are also covered. The lectures will be supplemented by homeworks utilizing the PowerWorld simulation package, including laboratory exercises investigating gaming in power markets and group mini-projects.
Design and Manufacturing Sector Course	This course introduces students to the global process and business side of the Product Design and Manufacturing sector and provides an overview of various types of products/manufacturing systems. The course includes a seminar series from manufacturing sector executives and other key stakeholders from industry and research organizations. Topics covered include: overview of design and manufacturing, product development overview, global perspective of manufacturing systems, business overview of a few manufacturing sub-sectors like space,

	automotive, aerospace, space, heavy equipment and others.

The three courses presented above have essentially the same objective, which is to develop, for the students concrete means to integrate technology and business perspectives in order to open for them new avenues of development for their career. However, there exist some differences in the approach for each. The Space Sector Course is strongly aligned on the Systems Thinking approach which is a very important component of this business sector; the Power Markets Sector Course also combines technology and business perspectives but offers to the students the opportunity to simulate the negotiations in power markets which is an essential element in this domain. The Design and Manufacturing Sector Course covers effectively a number of industrial sectors and aims to develop for the students an overall view of the technologies and systems involved for the design and manufacturing of concrete products as well as give them some understanding of the critical business processes involved in both product development and the physical product realization.

In order to support students in carrying out the assignments and capturing a holistic picture by applying the systemic view on the entire industrial sector, the Course Instructors conduct a number of workshops related to the assignments preparation.

CASE STUDY: SPACE SECTOR COURSE (SSC)

Syllabus

The Syllabus of the SSC examines the space sector through three different lenses: sub-sectors, technologies, and organizations. Such an approach is supported by different lectures, for example, on Earth Observation and geodesy; Launch services and markets; Space science payloads and missions; Space Policy; Space Sector Agencies, Organizations and Plans; “New Space”; Space Robotics; and others. Figure 1 reflects the Space Sector Course in respect to the Skoltech Learning Outcomes Framework (Crawley et al., 2013) built on the CDIO principles. This Framework places a much more important focus on the Leadership in Innovation at the postgraduate level, which is at the heart of the existence of Skoltech. The general Framework is built on the four UNESCO pillars and fundamental dimensions of learning.

The Framework presented in Figure 1 has four key topics and their subtopics. The SSC covers such subtopics as (see Figure 1):

- Knowledge of innovation and entrepreneurship (subtopic 1.3)
- Interdisciplinary thinking, knowledge structure and integration (subtopic 1.4)
- Cognition and modes of reasoning (subtopic 2.1)
- Attitudes and learning (subtopic 2.2)
- Relating to others - communication and collaboration (entire topic 3)
- Making sense of global societal, environmental and business context (subtopic 4.1)
- Visioning - invention new technologies through research (subtopic 4.2)
- Delivering on the vision - entrepreneurship and enterprise (subtopic 4.5)

The content of SSC reflects on the need to meet each learning outcome indicated above and in Figure 1.

According to Crawley et al., “system is a set of elements or entities, and their relationships, whose functionality is greater than the sum of the individual entities” (Crawley et al., 2015). In our paper we apply this definition to consider the Space Sector “holistically” as the system. We first outline the elements (or entities) of the Course. At the next step we define the relationships among these elements. After this we explain how the sum of these individual entities and the relationships between them brings the value delivered through SSC – acquiring the learning outcomes highlighted in Figure 1.

1. DISCIPLINARY KNOWLEDGE AND REASONING

UNESCO PILLAR: LEARNING TO KNOW

1.1 KNOWLEDGE OF MATHEMATICS AND SCIENCES
1.2 KNOWLEDGE OF APPLIED SCIENCE AND ENGINEERING SCIENCE
1.3 KNOWLEDGE OF INNOVATION AND ENTREPRENEURSHIP
1.4 INTERDISCIPLINARY THINKING, KNOWLEDGE STRUCTURE AND INTEGRATION
1.5 KNOWLEDGE AND USE OF CONTEMPORARY METHODS AND TOOLS

2. PERSONAL ATTRIBUTES – THINKING, BELIEFS AND VALUES

UNESCO PILLAR: LEARNING TO BE

2.1 COGNITION AND MODES OF REASONING
- Analytical reasoning and problem solving
- System thinking
- Creative thinking
- Decision making (with ambiguity, urgency etc)
- Critical thinking and meta-cognition

2.2 ATTITUDES AND LEARNING
- Initiative and the willingness to take appropriate risks
- Willingness to make decisions in the face of uncertainty
- Responsibility, intensity, perseverance, urgency and will to deliver
- Resourcefulness, flexibility and an ability to adapt
- Self-awareness and a commitment to self-improvement, lifelong learning and educating

2.3 ETHICS, EQUITY AND OTHER RESPONSIBILITIES
- Ethical action, integrity and courage
- Social responsibility
- Equity and diversity
- Trust and loyalty
- Proactive vision and intention in life

3. RELATING TO OTHERS – COMMUNICATION AND COLLABORATION

UNESCO PILLAR: LEARNING TO WORK WITH OTHERS

3.1 COMMUNICATIONS
- Communications strategy and structure
- Written, electronic and graphical communication
- Oral presentation and discussion
- Inquiry, listening and dialogue

3.2 COMMUNICATIONS IN INTERNATIONAL ENVIRONMENTS
- Communications in English in scientific, business and social settings
- Effective interaction in different cultural and international settings

3.3 TEAMWORK
- Forming effective teams
- Team operations and project management
- Team coordination, decision-making and leadership
- Team growth and evolution
- Technical and multidisciplinary teaming

3.4 COLLABORATION AND CHANGE
- Establishing diverse connections and networking
- Appreciating different roles, perspectives and interests
- Negotiation and conflict resolution
- Advocacy
- Bringing about intentional change

4. LEADING THE INNOVATION PROCESS

UNESCO PILLAR: LEARNING TO DO

4.1 MAKING SENSE OF GLOBAL SOCIETAL, ENVIRONMENTAL AND BUSINESS CONTEXT
- Appreciating the potential and limitations of science and technology, their role in society and society's role in their evolution
- Taking responsibility for sustainable development, including social, economic, environmental and work environment aspects
- Understanding the technical products, systems and infrastructure of the sector
- Understanding the enterprise – culture, stakeholders, strategy and goals
- Understanding the business context – markets, policy and ecosystem of the sector

4.2 VISIONING – INVENTING NEW TECHNOLOGIES THROUGH RESEARCH
- The research process – hypothesis, evidence and defense
- Basic research leading to new scientific discovery
- Research aimed at developing new technologies
- Imagining utility of new science and technology
- Developing concepts and reducing to practice

4.3 VISIONING – CONCEIVING AND DESIGNING SUSTAINABLE SYSTEMS
- Identifying stakeholders need and wants
- Identifying and formulating objectives and goals
- Conceiving and architecting products and services around new technologies and identifying their impact
- Disciplinary and multidisciplinary design for sustainability, safety, aesthetics, operability and other objectives
- Understanding the technical context and ecosystem of the product or service
- Design process management, including planning, project judgment and effective decision-making

4.4 DELIVERING ON THE VISION – IMPLEMENTING AND OPERATING
- Designing and optimizing sustainable and safe implementation and operations
- Manufacturing and supply chain operations
- Supporting the system life cycle including evolution and disposal
- Implementation and operations management

4.5 DELIVERING ON THE VISION – ENTREPRENEURSHIP AND ENTERPRISE
- New venture conceptualization and creation
- Financing product development and new ventures
- Building and leading an organization and extended organization
- Initiating engineering and development processes
- Selling, marketing and distributing products and services
- Understanding the value chain – the innovation system, networks and infrastructure
- Managing intellectual property and respecting the legal process

Figure 1. Skoltech Learning Outcomes Framework (Crawley et al., 2013)

Besides the domain-specific topics focused on knowledge acquisition, we uncover the skills-based tools, such as system thinking, critical thinking, the economics of a firm, how firms compete and the value chain in the development of a product. These universal skills aim to provide the coherent knowledge acquisition and skills development. For example, the lecture on critical thinking supports the students to properly analyze the content of lectures, videos and documents with a set of well-established criteria. The miniguide on Engineering Reasoning (Paul et al., 2013) is used as a reference in concrete assignments.

Figure 2 summarizes the high-level architecture of the SSC in OPCloud modeling language (Dori et al., 2019). The ultimate goal of the course is to support Students in meeting Learning Outcomes. The process “Acquiring” changes the state of the Learning Outcomes from state “not acquired” to “acquired”. The instrument that is used to meet those learning outcomes is the “Space Sector Course” built upon the “CDIO Framework”. The utility of the modeling representation is that it allows to comprehensively outline the architecture of the course, and as it will be shown later – to define the core Course’s elements and their relationships.

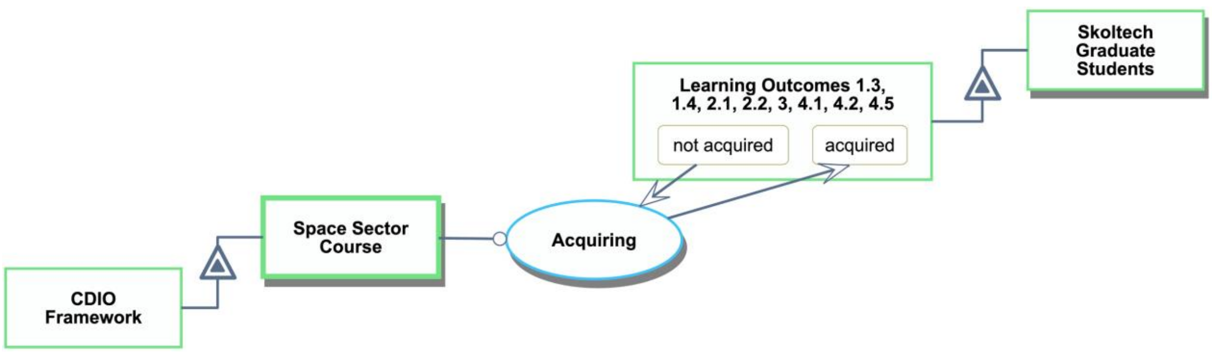

Figure 2. Holistic View of SSC. Rectangles represent objects, such as “Skoltech Graduate Students”, “Learning Outcomes” (with the numbers reflecting the specific topics/sub-topics from Figure 1), “Space Sector Course”, and “CDIO Framework”. An oval denotes a process, for instance, “Acquiring”. “Roundtangles” are encoding the states, such as “not acquired” and “acquired”. The triangle inside a triangle means that, for example, “Learning Outcomes” is an attribute of “Skoltech Graduate Students” implying that upon completion of SSC the students will acquire the required knowledge and skills.

Elements of SSC

The SSC consists of cross-disciplinary lectures (such as Critical Thinking Lecture, System Thinking Lecture, Economics of a Firm, and Value Chain Analysis as specified in Figure 3), sectoral lectures (for example, Space Sector Agencies and Organizations, Launch Services and Markets, and Space Science), and assignments (Assignment 1: System Map, Assignment 2: Critical Thinking’s Lecture Analysis, Assignment 3: Business Plan Analysis). Note that the elements appearing in Figure 3 are representative and are not completely demonstrating the full set of lectures and assignments within the SSC.

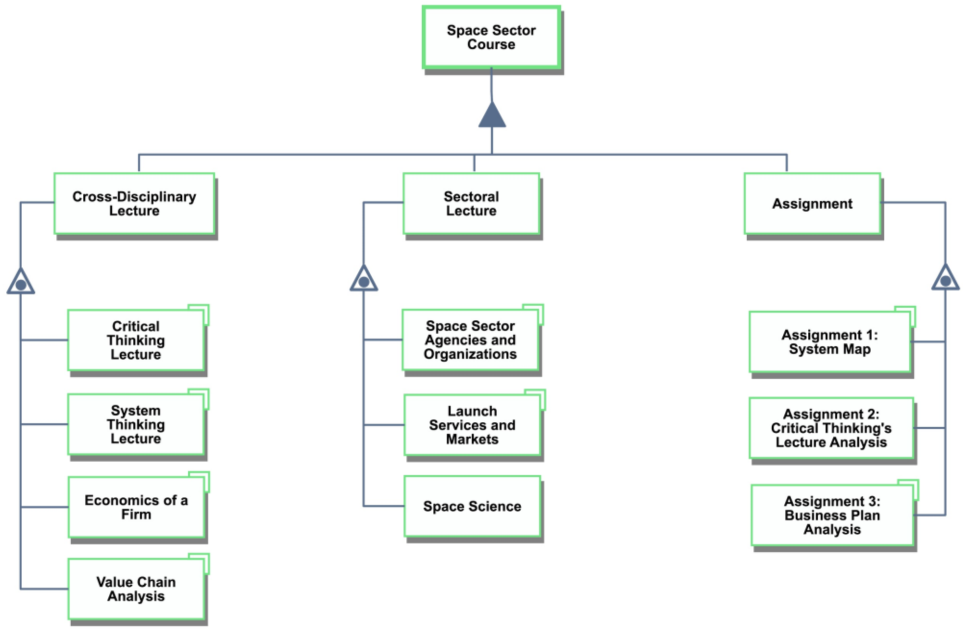

Figure 3. The SSC and its elements: cross-disciplinary lectures, sectoral lectures, and assignments

Relationships among and within the elements of the SSC

Figure 4 represents the relationships between the elements (cross-disciplinary and sectoral lectures and assignments) of the SSC. For example, the left-hand side of Figure 4 informs that Assignment 1 is dedicated to System Map. This Assignment is using the information from the sectoral (Space Sector Agencies and Organizations) and cross-disciplinary lectures (Critical Thinking lecture and System Thinking lecture). All of these lectures are held before the Assignment 1. In the same manner, the cross-disciplinary lectures on Economics of a Firm and Value Chain Analysis, as well as the sectoral lecture on Launch Services and Markets are all used to support the students with the Assignment 3 dedicated to the Business Plan Analysis.

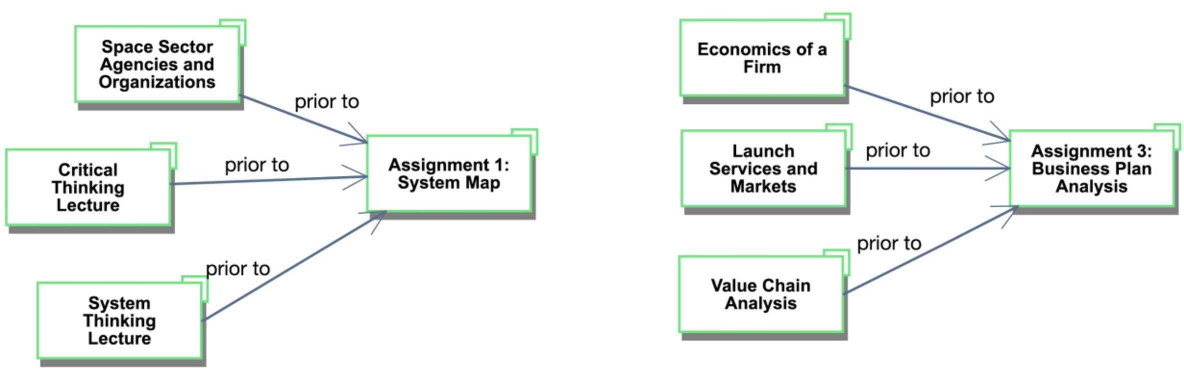

Figure 4. Example of the relationships between the elements of the SSC

DISCUSSION

During more than 5 years of successful implementation at Skoltech, the SSC proved itself as a practical and useful course for graduate-level students. The course has been held 5 times and was delivered for more than 120 students at Skoltech. The SSC was once held in parallel with MIT class (16.S899 in 2017) in the AeroAstro Department. This has led to joint collaborative work of students followed classes at Skoltech and at MIT.

Upon completion of the Course, students are exploring and proposing concrete entrepreneurial projects – either hardware or software start-up projects. Over the course of the Class, students have presented around 50 projects, around 10% of which became entrepreneurial ventures after the successful completion of the Class.

A practical utility of the SSC and any other Sector Course at Skoltech is that they help students to shape a holistic understanding of a number of sector-related questions. Among such questions are "Who are the main stakeholders in this sector?"; "How profit is achieved in this sector?"; "Which resources are critical for each stakeholder and how the process of resources' exchange is organized?", "Who are the most successful commercial actors in this sector?"

Skoltech recruits students broadly, from multiple disciplines related to science and technology. In light of this, a Sector Course is a unique perspective to support students in acquiring knowledge and skills related to a whole sector's lifecycle. In this capacity a Sector Course reflects Standard 1 (the context) of the CDIO Standards 3.0. SSC is also aiming at achieving the specified learning outcomes, thus, covering the Standard 2 (learning outcomes) of the CDIO Standards 3.0. The students are using the acquired knowledge and skills to propose the commercially viable project at the end of the course. This involves the consideration of the proposed project from a variety of disciplines – not only purely engineering, but also economical and societal ones. All of these support Standard 7 (integrated learning experiences). In accordance with Standard 8, students are also asked to assess the lectures of stakeholders based on the principle of critical thinking and they also have to develop a project of their own in teams based on the content of the course.

In our paper we explore the experience of running the SSC at Skoltech. We have chosen this course (out of 2 others – Power Markets Course and Design and Manufacturing Sector Course), because it was conducted more often than the other two.

CONCLUSION

This paper discusses a general framework for a particular type of course which we call a Sector Course in any domain of interest. To develop such a framework, three courses run at Skoltech were overviewed: Space Sector Course, Power Markets Course, and Product Development and Manufacturing Course. As a case study, the Space Sector Course has been chosen and described in detail. We covered the syllabus, lectures/seminars, and the relationships among and within these elements aiming at shaping students' knowledge and skills in accordance with the CDIO approach. Key learning outcomes from the Course are concerned with the students' ability to capture the entire sector, by acquiring the knowledge required for the integration of engineering and business perspectives of the Space sector. On the one hand, this process meets the Skoltech learning outcomes framework. On the other hand, it leads to a very practical outcome, as the students start to see potential employers, or potential fields for new startups.

One of the main issues to develop such a Course is to be able to invite a wide variety of specialists from the field, who can provide from their combined contributions a global perspective on an industrial sector. Another issue is that there should be proper interaction between the Course Instructors and invited guest lecturers. This is important to facilitate the alignment of their lecture with the global systemic framework.

Upon successful completion of the Sector Course, the students acquire the knowledge and professional skills required to consider innovation and entrepreneurial paths for their careers. This is achieved through different channels, among which are: holistic view of the Sector and integration of the lectures and assignments. We also try to invite guest lecturers, who are alumni of this Course and have founded and/or are currently working on a Space-related startup.

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BIOGRAPHICAL INFORMATION

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