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SYSTEMS ENGINEERING: AN INTERDISCIPLINARY CHALLENGE

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Abstract

Systems Engineering is a very wide interdisciplinary subject. In education it is a fine balance to make it general enough and at the same time allow for technical depth. To be perceived as a useful subject by students that have little idea of the real problems of engineering of complex systems this pose a sever challenge. The approach presented here is to present a toolbox of useful tools that are representative and that also can be used in more technical applications. There is also a difference of teaching Systems Engineering as a course in a general engineering program and in a program that is centered around this concept. In this paper it is discussed how this can be implemented in a Master Program in Aeronautical Engineering and in Master Program in Engineering and Innovation Management.

1 Introduction

Systems Engineering has become an increasingly important discipline in development of complex products, services and processes. The word is, however, a bit ambiguous and often misunderstood since there are many schools of thought about what it really is. Furthermore, it is easy to fall in the trap to think that another person means the same thing as yourself when speaking about Systems Engineering, while in reality it could mean very different things to different people. Systems Engineering is such a wide discipline that one person usually can only grasp a subset and interpret it from his/her perspective. Systems Engineering can be classified as a subset of Systems Science (or Systems Theory) see, Hieronymi [2] where it is stated "The many streams within systems science have diversified perspectives, theories and methods, but have also complicated the field as a whole". There is a number of partly overlapping fields within the broad scope of System Science/Theory, such as: Systems Engineering (SE), [3], [4], Systems of Systems (SoS), [5], System Dynamics (SD), [7], Dynamical Systems Theory [8], Cyber Physical Systems, [6], etc. In addition, there is also an overlap to Engineering design, and Design Science, with their own academic communities. It is perhaps unavoidable that this situation occurs since they are sprung from many unrelated fields, some more related to software, other to physical products, and other to e.g. defense systems of systems.

This means that great care has to be taken to identify what parts are the ones that should be considered in e.g. a Master program. It also means that care has to be taken if e.g. Systems Engineering and Engineering Design are to be taught in the same program so that overlapping part, represented in different way, will appear inconsistent and confuse students.

Therefore, the aim of this paper is to analyze the effort of joining different knowledge in order to reach innovation. We ask how system engineering can be taught in two different contexts.

As a way to get some answers for this question, we have proposed a case of two totally different programs, but that use systems engineering as a backbone.

This paper is organized as follows. In section 2, we presented a brief overview of systems theory with the different spectrum of disciplinarity. In section 3, we described the method used to build the paper, Finally, in section 4 we reported our findings while in section 5 we discussed our findings and the conclusion.

2 Systems theory

According to Heylighen and Joslyn [1], systems theory can be defined as the “transdisciplinary study of the abstract organization of phenomena, independent of their substance, type, or spatial or temporal scale of existence. It investigates both the principles common to all complex entities, and the (usually mathematical) models which can be used to describe them”

In other words, instead of taking individual components (subsystems) of an entire system, systems theory is concerned with the system architecture and the connections between the subsystems, which, in the end, will conjoint the system as a whole. This integrative architecture creates a system, which, on the other hand, is independent of the specifics subsystems.

Another idea of systems can be seen in the movement from an insular discipline that moves towards agglutinating other disciplines to the point that they become a unified field. Stember has proposed a typology within and across discipline [9].

- Intradisciplinary: working within a single discipline.
- Multidisciplinary: people from different disciplines working together, each drawing on their disciplinary knowledge.
- Crossdisciplinary: viewing one discipline from the perspective of another.
- Interdisciplinary: integrating knowledge and methods from different disciplines, using a real synthesis of approaches.
- Transdisciplinary: creating a unity of intellectual frameworks beyond the disciplinary perspectives.

For some, the definition of interdisciplinary and transdisciplinary are not straightforward. Interdisciplinary is focused on a single subject of investigation which can be understood using knowledge coming from different disciplines. So, there is a single question – or a limited set of research questions – which can be understood by integrating knowledge and methods from different disciplines.

On the other side, transdisciplinarity encompass the possibility of a variety of research questions they might be understood only outside the boundaries of the singles disciplines but generating an overall knowledge which embraces all the disciplines.

In figure 1 we can visualize the differences in concepts of disciplines and the attempt of achieving a unified field that embraces all of them.

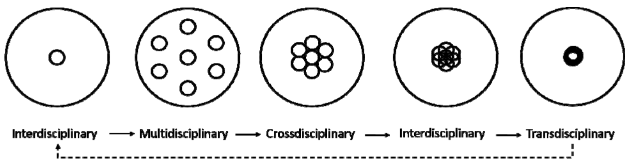

Fig 1. Evolutionary progression for a discipline, adapted from [10].

3 Research design

A case study approach forms the methodological framework of this study. In this paper we explore the ways in which the curriculum of two different program use different forms of systems engineering to create integration.

Given the cases were chosen due to its specific contexts, the connections of the authors with the subject and the data collection were made possible through participant observation mechanisms.

Data were analyzed and interpreted trough the lenses of systems theory and interdisciplinary theoretical framework.

4. The two cases

At Linköping University (LiU), there is Master Program in Aeronautical Engineering where a specialization within Aircraft Systems Engineering is set up. This draws some inspiration from research at Aerospace System Design Laboratory (ASDL) at Georgia Tech, see e.g. [13]. The LiU master program specialization is a technical profile where the Systems Engineering part mainly is defined by two courses; one more general one in Engineering Systems Design, also open to other students, and one more specialized one in Aircraft Systems Engineering. At Federal University of ABC (UFABC) in Brazil, a new program in Engineering and Innovation Management has just opened its first class in 2016. This program is very much centered around the concept of Systems Engineering, Product Development, Innovation Management. Here the idea is to use students of different background, e.g. from technical to economics, to do real interdisciplinary projects. These two programs in a way can be said to represents two extremes.

Even though the two programs are very different, both approach systems engineering from the perspective of the different Stakeholders, and the differences can be understood from that. The most important stakeholders can here be said to be;

- University (policy and regulations)
- Teaching staff
- Industry
- Students.

In both programs, the curriculum was created by the teaching staff and their own background naturally play a key role. In the case of Aircraft Systems Engineering, the teaching staff is largely existing and have a similar academic background and a common ground in the typical subjects. The role of the systems engineering is then to provide the glue between these subjects. The industrial needs are quite clear since it is mainly defined by the needs of the aeronautics industry. The students also have somewhat similar backgrounds.

In the case of the Engineering and Innovation Management, the program was defined by a very small group of professors, attracting researchers intrigued by the program, resulting in a much more differentiated background among the teaching staff.

Furthermore, the industrial needs in Brazil are not so clearly articulated. This means that the program was much more free in its gestation, and also have to be more flexible to accommodate needs that will be apparent when the program has been running a couple of years. One difference is related to the different university systems. In Brazil the Bachelor level is more extensive than in Sweden and the Master Program has a full academic year with research work, while in Sweden the research project is only allocated half an academic year.

This means that there is a larger possibility to have the education more individually tailored through the project, with respect to the widely different background of the students, and also with the competence of the professors.

4.1 Aircraft Systems Engineering

This is a specialization within the Aeronautical Engineering Master at LiU. This is an international master program with predominantly international students, although Swedish students represents a considerable part.

This is a very technical program recruiting students mainly students with a background in Mechanical or Aeronautical Engineering. Usually these students have a background with analytical subjects but not so much integrative subjects. The idea with the Systems Engineering Specialization is to build on this background by picking up the subjects and put them together to look at whole systems. This is a bottom up approach where the student is gradually moved to higher system levels. There are also courses in Aircraft Design developing skills and domain knowledge in this area not least through a group project in the last year. There are also two courses that are explicitly systems oriented, where the first, Engineering System Design, serves as an introduction to the more technical aspects of Systems Engineering, introducing some tools, and Aircraft Systems Engineering, where these are applied.

4.1.1 Engineering System Design Course

This started as a 6ECTS credits course at the Master level for Mechanical Engineering Students. It has over recent years shifted into becoming more oriented towards aerospace through the examples used in the course.

The name of the course reflects the fact that it is centered towards technical and analytical techniques. Rather than being centered around a Systems Engineering process it is centered around tools and methods on a more fundamental level. This is because students with no work experience have very hard to see the use of a process. Instead this is experienced in a project course, and research project, in the second year. Because of the time constraint in the course, the selection of tools introduced are also selected in order to fit together into a single

narrative, and should be useful in the subsequent courses. These are described in Krus [15]. Furthermore, these are tools that are useful in their own right even outside the context of systems engineering. It can be argued that tools that can be introduced incrementally and still be useful, have a greater chance to get acceptance, than those that relies on the implementation of a full set of organization and tools for systems engineering.
The V-model for system design is central in Systems Engineering (e.g [3]).

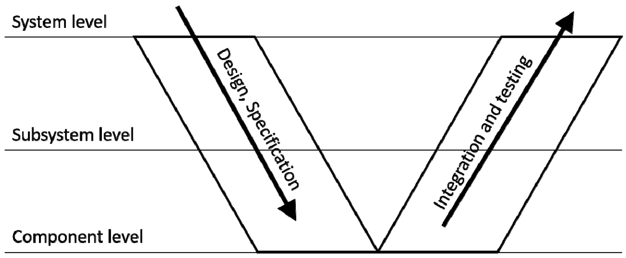

Fig 2. System development V-model. (Loosely after [3]).

However, in order to be able to illustrate the whole loop at least in principle, integration and testing is done through executable models. This lead to the modified V.

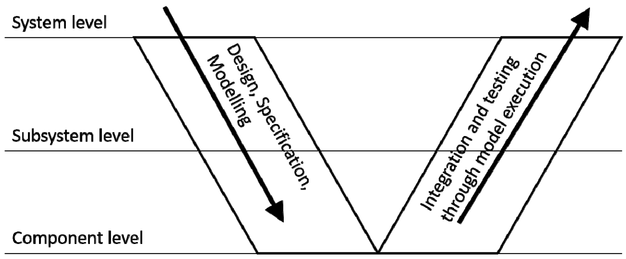

Fig 3. Modified V-model with model execution.

The course is divided in the following areas; Functional decomposition, modelling for conceptual design, design relations, sensitivity and robustness analysis, design optimization and fault tree analysis.

Requirements

Here the house of quality from Quality Function Deployment (QFD) is introduced. This has been implemented in an open-source tool for Excel that is connected into a tool suite also for sensitivity analysis, robustness analysis and functional correlation analysis. SysML, can also be considered, but was left outside the scope of the course since there is no straightforward coupling to executable models.

Functional Decomposition and Modelling

For functional modelling Funcitonal Flow Block Diagrams (FFPD) are used [4]. The main reason is that they are available for simulation in the Hopsan simulation package. In this way providing a link between functional description with states and a full simulation model. However, SysML is a standard that is also very suitable for this, although this might change since there is no direct link to system simulation, although there are experimental ones, e.g. for Open Modelica.

System Simulation

Something that is not so much emphasized in either INCOSE or NASA is the need to close the design loop with modelling and analysis, e.g. through simulation. Without this, there cannot be optimization or sensitivity analysis and furthermore, detailed knowledge of design relations cannot be achieved. Here this is emphasized and implemented by introducing system simulation software at an early stage. Although many types of simulation or calculations can be made to close the design loop, system simulation has a special role, [15].

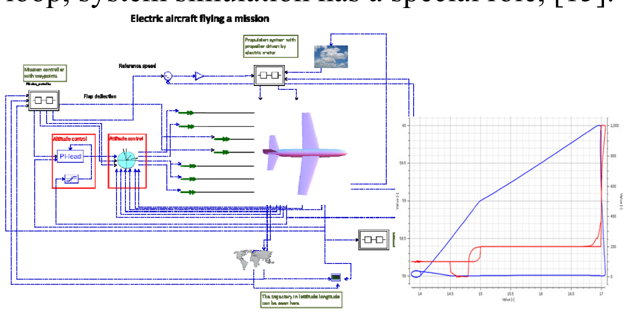

Fig 4. Simulation model of UAV with electric propulsion system executing a mission.

Through system simulation functional behavior can be demonstrated, and interaction between subsystem studied. Furthermore, system simulation can be used to generate boundary conditions, e.g. loads for more detailed analysis in other dedicated tools. There are many tools, such as Matlab™, AMESIM™, Simulation-X™, and also open source tools such as OpenModelica [16] and Hopsan [17], [18]. A simulation model of an electric aircraft executing a mission is shown in Figure 4. This is an example of a systems engineering task including definition of requirements from the mission specification through (a simplified) design and execution of the model through simulation. In this way it is demonstrated how all elements have to work together to fulfill the mission.

Design relations, Sensitivity, Functional Correlation, and Robustness Analysis

A central concept in Systems Engineering is the relation between design parameters and the functional requirements, [12]. Having a proper understanding about the influence of different parameters, components, and subsystems on the functional characteristics of the product is a basis for doing a proper tradeoff in a system design, [14]. Furthermore, using the sensitivity analysis it is also possible obtain the correlation between functional characteristics showing conflicting and coherent functional requirements.

Related to sensitivity analysis is Robustness Analysis where the influence of uncertainties and variabilities of parameters, and variables outside the control of the design is studied.

System Optimzation

With a clear understanding of the relation between requirements and functional characteristics, it is possible to formulated the system objectives, and using an executable system model it is possible to optimize the system for various scenarios. System optimization is also important in the sense that it can be used to validate requirements and models. Very often strange results can appear as a result of omitted requirements or over simplification in the models.

Fault Tree Analysis

The functional decomposition can also form the basis for Fault tree analysis. In aircraft design safety is very often a driving requirement in the design. I.e. it is the single most important requirement, and in many ways dictate the selection of system concept. No course in systems engineering can therefore be without this.

4.1.2 Aircraft System Engineering Course

This is a new course. Aircraft Systems Engineering is a more domain oriented course, dealing with integrated aircraft systems, E.g. flight dynamics, flight control, and basic aircraft systems. Furthermore, various aspects of mechatronics for design, operation and testing, of small unmanned aircraft will be included. This is in order to give the necessary background to design, build and test aircraft concept in a subsequent design project course.

4.2 Engineering and Innovation Management

This is a Master's Degree program hosted at the Federal University of ABC, UFABC and approved by CAPES' Interdisciplinary committee, a section of the Brazilian Ministry of Education in charge of graduate programs. It is important to remember that UFABC was created from scratch in 2005 as part of a new pedagogical model where the faculty body are not organized in departments, but center that congregates a faculty body with diverse educational background.

This program accepts students from widely different backgrounds from engineering to economics, computer science, and literature. In this way, following the project-based learning pedagogical method, it is expected innovative solutions based on the integration of interdisciplinary knowledge addressing contemporary societal problems.

This program has not a focused application area, but seeks projects in fields such as health, energy, transportation, industrial, where an interdisciplinary perspective is a natural part of the problem solving.

In order to prepare the students for these projects, the program offers courses that has been considered an integrative architecture for the a multi and crossdisciplinary body of knowledge that results in the Interdisciplinarity necessary to achieve innovation. Courses in technology and engineering design aims to understand how technological systems can be strategically designed, developed and integrated, considering not only the technical progress, but also the socio-cultural, cognitive, and environmental dilemmas.

Therefore, in order to develop systems that are technically competitive, they must incorporate new technologies that are integrated, refined and tested. From a marketing point of view, it is important to consider design, to make it user friendly and its disposal respects the environment. Finally, it must present cost-benefit in face of observed constraints.
At the same time, this program offers courses in management of technology and innovation. These courses comprise a body of knowledge necessary to manage innovation, taking into account strategic, organizational, and economic aspects, both at the firm as the market level as well.
Therefore, it is necessary to foster analytical skills to understand the dynamics of technological innovation within and in organizations. It is important to comprehend how to develop the tools that guide decision-making and assist in the formulation of solutions that transform technological opportunities into innovation. So for those involved in management it is essential to understand the processes that support technological innovation, whether a user or producer of it.

4.2.1 Fundaments of Systems Engineering

This is a mandatory course in Systems Engineering, which is partly based on the Engineering Design Course at LiU. The aim of the course is to analyze the components of integration between the different specialties necessary to achieve the design and development of complex engineering systems.

4.2.2 Theory and Practice of Design

Theory and Practice of Design provides a basis for understanding disciplinary and interdisciplinary dialogues in design research, providing theoretical, empirical and methodological sources for the practice of design. In Analytical Methods for Designers the purpose is to study how the properties of systems and subsystems can be provided, described, evaluated and optimized in an efficient and systematic interface design.

4.2.3 Cognitive Engineering

In *Cognitive Engineering*, the purpose of the course is to provide the necessary basis for understanding the integration of technological capabilities and human cognitive limitations in sociotechnical systems.

4.2.4 Interactive Design

Interactive Design has the purpose to apply the methods and tools that allow to represent the behavior of a system in its real environment

4.2.5 Strategic Management of Innovation

The purpose of the course in *Strategic Management of Innovation* is to analyze emerging practices on the dynamics of interactions between patterns of technological change and its intersection with the organizational strategies that will result in innovation.

4.2.6 Management of Technology

Management of Technology discusses the critical elements to innovate along the technological frontier. For this, the technology managers need to have an overview of all the technological landscape and its main evolutionary trends and how they converge with the portfolio of products/services/ processes.

4.2.7 Innovation Law

Innovation Law course goal is to critically analyze the principles of technology transfer, and intellectual property rights. An important implication of this process is the issue of communication between companies and academia.

4.2.8 Financing Innovation

In *Financing Innovation*, the aim is to provide the instruments needed to understand the relationship between the evolution of financial markets and economic performance. Thus, it is expected to gain understanding of the sources of funding and its implications on the dynamics of innovation.

4.2.9 Technology Marketing

For the course in *Technology Marketing*, the goal is to provide a detailed view of the marketing strategies used in the processes of creating and marketing products and services in technology markets.

4.3 Student project

As for an initial project, students were asked to propose solutions for the concurrent outbreak of dengue, chikungunya, and zika virus infections. This is an example of a highly interdisciplinary problem and a range of widely different concepts to address the problem were developed. These ranged from more precise diagnosing, fighting the mosquito in innovative ways, to using apps to gather information about the virus using gamified applications for smart phones.
In addition, there are student's research projects initiated such as Autonomous Bus Transportation. The general goal of this work is conceive the main functions of an autonomous Bus Rapid Transit (BRT) using techniques of system engineering. The idea is to specify the safety requirements in order to identify feasible solution to be implemented.
In a joint research between the authors, we have proposed an evaluation on technological change of complex systems. Therefore, in order to map the domains of valid requirements, we examined the increasing demand for electrical power systems contents for aircraft, as a way to demonstrate the criticality of technology and the comfort zone domain for aircraft propulsion.

5 Discussions and Conclusions

Systems Engineering is a very wide and hard to grasp discipline, and therefore there are many different approaches depending on context and application. Nevertheless, it is being recognized as an increasingly important discipline explicitly sought after by at least advanced industry, and also useful to others. It is interesting to note that, although this discipline in some sort have been practiced implicitly as least since the building of the pyramids, it has not become recognized as a discipline of its own right until recently, and even now, it is argued what it is really is about. In the programs described in this paper the theoretical foundation is in System Science/Theory applied to innovation in products, services and processes.
In this paper two different approaches to Master's level Systems Engineering programs have been discussed. Each is the result of different requirements. One is within a single area (Aircraft Systems Engineering) with students of a rather homogeneous background. The other accept students, and draw its strength from having students, of different backgrounds to be able to work truly multidisciplinary. In the first case, the objective is to educate Aeronautical Engineers with an understanding of Systems Engineering. In the other the objective is to produce people with a profound Systems Engineering and Management understanding, that can be used over a wide range of application areas. In the latter case it is understood that the management part is important since these people will bring people together, and they will manage the skills of others. (E.g. they should have no problem working with professionals from the Aeronautical Systems Engineering profile.) It can be concluded that there is not one kind of Systems Engineers, the context of the program, has to be well understood.

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