SYSTEMS THINKING IN A MECHANICAL ENGINEERING PROGRAM

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ABSTRACT

In engineering programs, systems thinking capability has been promoted for a long time. The capability of students to apply various systems thinking approaches is not only supported by educational staff, but also highly required by various employers. The aim of the study is to investigate the inclusion of systems thinking aspects in the Mechanical Engineering program at Linköping University. Two research questions address this aim. According to involved teachers, (1) What aspects of systems thinking are included in the Master Program in Mechanical Engineering?, and (2) What teaching and learning activities concerning systems thinking are included in the Master Program in Mechanical Engineering? Empirical data was gathered through focus group interviews with involved teachers from two Master profiles. The results indicate that systems thinking is present in the respective Master profiles, however not explicitly communicated with the students. Systems thinking is often coupled with disciplinary knowledge, which supports CDIO standard 3. Some examples of how systems thinking is taught relating to disciplinary knowledge (CDIO standard 7) were presented by the teachers. Examples of teaching activities specifically aimed at systems thinking were however missing, alongside examination of systems thinking in particular.

KEYWORDS

Systems thinking, Teaching and learning activities, Master profiles, Applied Mechanics, Mechatronics, Standards: 3, 7

INTRODUCTION

The world is growing more and more complex and fast-changing, which makes it a challenge to prepare today's students for decades of working life. In engineering programs, systems thinking capability has been promoted for a long time. Considering the growing complexity in practically all societal contexts, systems thinking has also recently gained increased attention as a means to bring order to and improve the understanding of a wide variety of contemporary phenomena. The capability of students to apply various systems thinking approaches is therefore not only supported by educational staff, but also highly required by various employers.

Against this background, the board of Mechanical Engineering and Design at Linköping University decided to investigate how the engineering programs under its supervision address systems thinking, and how the modules and the program support the students' development of a systems thinking capability. The engineering programs at Linköping University are all designed and managed in line with the CDIO framework. Hence the connection between the CDIO framework and systems thinking is of interest to the board.

In response to the urge to investigate systems thinking and the relation to CDIO, the aim of the study is to investigate the inclusion of systems thinking aspects in the Mechanical Engineering program. Two research questions address this aim:

RQ1: What aspects of systems thinking are included in the Master Program in Mechanical Engineering (cf. CDIO standard 3)?
RQ2: What teaching and learning activities concerning systems thinking are included in the Master Program in Mechanical Engineering (cf. CDIO standard 7)?

RESEARCH ON SYSTEMS AND SYSTEMS THINKING IN EDUCATION

There are many different definitions of systems and systems thinking, because both concepts have been used in such diverse fields as biology, ecology, health science, environmental and climate science, chemistry, technology and engineering, computer science, geosciences, logistics, complexity science, economy and management, and social science. In this paper, we will adhere to a broad definition of a system taken from Ingelstam (2012): A system fulfils a particular purpose, it consists of components, relations or connections between these components, and has a system boundary. Beyond the system boundary is the surrounding, which may interact with the system but is not part of it. Systems thinking could refer either to a scientific discipline, a methodology or a skill set (Elsawah, Ho, & Ryan, 2022; Oskarsson, 2019). With Ho (2019), in this paper we define systems thinking as "a set of skills for understanding, analyzing, and working with systems consisting of multiple interconnected elements and exhibiting emergent properties" (p. 2764).

Students of varying disciplines and of all ages find it difficult to understand systems, so systems thinking is generally not well developed (Booth Sweeney & Sterman, 2000; 2007). As regards technological and engineering systems, students gain a deeper understanding of systems as they grow older, especially regarding the included components. However, there is no significant difference between younger and older students, or student teachers. In this regard, control mechanisms and flows of information are particularly difficult to grasp, as is the role of humans in and around a technological system. Non-linear systems are also generally more difficult to understand than linear systems (Arbesman, 2017; Hallström & Klasander, 2020). It is apparently effective to study aspects or layers that are common to more than one system, thereby allowing for structured comparisons between systems. This, in turn, is important for students to be able to generalize systems knowledge (Hallström, 2022).

Such generalized knowledge could be called systems thinking, in line with the above definition (Hallström & Klasander, 2020; Ho, 2019). Research about students' systems thinking shows, for example, that regardless of discipline undergraduate students' systems thinking skills can be improved with appropriate teaching interventions (e.g. Elsawahet al 2022; Rosenkränzer, Kramer, Hörsch, Schuler, & Riess, 2016). Rosenkränzer et al (2016) also suggest a model outlining a progression for deepening and improving systems thinking skills, which has been adjusted specifically for technological and engineering systems by Engström & Svensson

(2022). However, as Elsawah et al (2022) conclude in a recent study, “which teaching approaches and methods (e.g., mapping, simulation) are most effective for promoting systems thinking skills has not yet been determined” (p. 89).

RESEARCH DESIGN

At bachelor level the Mechanical Engineering program at LiU consists of compulsory modules. Thereafter, at Master level, the students follow one of ten specializations, so called Master profiles. Each Master profile has a defined set of modules, some of them mandatory, others eligible. Since the different Master profiles cover different content and are given by different teachers, we supposed that systems thinking would be treated differently between these profiles. Therefore, we focused our study on this later part of the program.

In consultation with the Program Director, we selected two Master profiles as our studied cases. These were chosen for the following reasons: focusing different parts of mechanical engineering, together they cover a broad view of the field; there was a preconception that systems thinking is treated differently in these profiles. A brief description of the two profiles is given in the following table.

Table 1. The studied Master profiles

Master profile	**# of compulsory modules**	**# of eligible modules**	**# of students per year**
Mechatronics	7	17	25-35
Applied mechanics	5	18	10-15

For each profile, or case, we studied module curricula to see how and to what extent systems thinking was expressed in the “expected learning outcomes” and “module content” in these documents. We informed the coordinators for each Master profile of the study. In consultation with them, teachers were selected for participation in focus group discussions in order to include a second-order perspective in the RQs. All teachers have long teaching experience and are examiners for one or more modules in the respective profiles.

The planning and conducting of the focus group discussions were informed by e.g., Bryman and Bell (2011), Dahlin Ivanoff and Holmgren (2017), and Wibeck, Dahlgren, and Öberg (2007). We prepared discussion themes with inspiration from Jackson and Hurst (2021) and used information from the reviewed curricula as input for the discussions. Before the sessions, the participants were informed about the purpose and setup of the study, their voluntary participation, and the anonymization and overall management of data (according to GDPR). Subsequently, they all consented to being part of the research study (Swedish Research Council, 2017). One of us acted as moderator, with the intention of letting the participants talk freely, but slightly steering the discussion to cover the prepared themes. The discussions were audio-recorded and thereafter transcribed. Some details about each discussion are provided in Table 2.

Table 2. The focus group discussions

Master profile	Participating interviewers	Participating teachers	Extension (minutes)
Mechatronics	2	6	87
Applied mechanics	3	3	73

A content analysis was performed, where we categorized relevant content from the discussions. As Eisenhardt (1989) and Braun and Clarke (2006) suggest, we started out with tentative categories, in this case inspired by Jackson and Hurst (2021). However, following Finfgeld-Connett (2014), we allowed for modifications of the categories, i.e., the analysis combined deductive and inductive elements. At least two of us made an individual analysis of each discussion, which after comparison were combined to an aggregated one.

RESULTS

The analysis of the focus group data yielded altogether six themes, of which two relates to RQ1 and four to RQ2.

The Nature of Systems Thinking

The interviewed teachers described a great variety of different systems – mostly technological – that were addressed in their teaching in the Mechanical Engineering program. They also reflected upon systems thinking: what it entailed for them and its presence in teaching in general.

Types of Systems

The teachers in the Mechatronics profile mentioned a number of different systems that are dealt with in their teaching, of which most are technological systems such as mechatronic, hydraulic, electronic, electro-hydraulic, mechanical, and automotive vehicles and systems. To a lesser degree they mentioned systems such as bridges, robots, medical technologies, as well as other types of systems like quarks, economic systems, political systems, and the climate system.

They also referred to different types of systems such as dynamic systems versus static systems, although they mostly taught about dynamic ones. There was also mention of open versus closed systems, as well as how different systems can be connected and/or entangled. The informants also claimed to go into detail about certain systems when teaching, in particular different types of control systems (e.g., technological systems or a human riding a bicycle), using concepts such as input – process – output, feedback, disturbance, regulator, servo, state, sensor, and component/s working together. The system boundary was also referred to when talking about what could actually be included in a system, for example: "*to us program code, algorithms and such are kind of part of the system*"; *"it is much about algorithms and such, and the control system. That is also part of [the system]"*.

The teachers in the Applied Mechanics profile discussed systems in a more implicit way, compared to those in the Mechatronics profile. They suggested that kinematics of rigid bodies and associated force analysis could be seen as an application of the systems concept, as it concerns parts that interact and generate movement.

Thermodynamic systems in general were put forward as typical systems, even though they are taught at the bachelor level. A concrete example was the gas turbine, which can be seen as a system in itself but also as part of a system interacting with a compressor and a combustion chamber. Finally, the human body was also suggested as a system. Modules that focus on the human body are offered both in solid and fluid mechanics.

Presence and Characteristics of Systems Thinking

When prompted, the informants in the Mechatronics profile referred to systems thinking as something that is a natural part of both research at the department and teaching within the mechanical engineering program. One teacher put it like this: *"Well I have been here for ages and systems and systems thinking, those are kind of mother's milk".*

Systems thinking was also mentioned as being practiced and trained among students during the program, and also as an outcome after having obtained the mechanical engineering degree. When prompted, the teachers could mention some kind of definition of systems thinking, for example: "*I think about this ability to actually picture something with boxes and arrows. Here is this part, these are interesting. And then there, I integrate with this part over here, which in turn integrates with this. So maybe we have kind of a feedback loop like this. To abstract a situation with boxes and arrows, that is systems thinking to me.".*

Another teacher put it like this: *"we have the system. And we have a kind of standard measurement, we are supposed to reach something. And what is often present in our world, the mechanical world […] there are always conflicts. In engineering problems we must make a trade-off. And there are inherent trade-offs all the time. And the more you make the system fit with reality, the more such conflicts well over you"*.

Yet another teacher focused on the system's boundaries: *"systems view entails different perspectives on the same item".* By putting the item of interest in relation to other items *"that is different models. And it is the same physical item. But that is another system's view. I made a limitation that is context related. And to me it is the context, the limitation that, so to speak, is the systems thinking*".

However, although systems thinking permeates the program and the Mechatronics profile on various levels, it is in practice mostly implicit both to teachers and students. One teacher thus described how he structured a module and included systems to promote students' systems thinking. By starting with one motor component and viewing it from various angles, and then putting it in the wider context of other motor components, he "built" the system for the students and thus in practice introduced the systems thinking.

A salient feature of the implicit promotion of systems thinking in the modules is the teachers' inclusion of aspects of modelling of systems. One of the aims of modelling is for the students to be able to distinguish between a model of a system and the actual, real system.

The informants in the Applied Mechanics profile agreed that the systems view was closely related to the nature of the problem at hand: *"Yes, in the end it depends on what the problem is about"*.

Overall, systems thinking was perceived as concerning how components interact with their context, or with another component or another system. Interacting systems were related to a holistic view and engineering thinking in general. Sometimes the teachers use the term model in parallel with system, where the system model is used for creating a mathematical model: *"Yes, well, the system is then, kind of, we take the reality and then we isolate it. And then we try to interpret it, or transfer it to a mathematical equation system. And that is the model"*.

The teachers also discussed that systems thinking is manifested through a collection of fundamental rules, and that systems thinking was represented by a set of methods for progressing analysis. Furthermore, the system boundaries were discussed among the teachers as important: *"And you have a small component, there is a fluid inside there, and then you draw the little system boundary, and decide what passes over the boundary here and there, energy and work and current. And there you have your system and system's boundary".* But the system boundary also has different significance among the modules on the profile: *"When you [in fluid mechanics] talk of systems it is very natural that something passes the system's boundary. It passes, thus integrates with the system's boundary. And that is not so obvious in [solid] mechanics, where you have a smaller detail like a link or a cogwheel, or something. So, in solid mechanics a system's boundary is seldom something to pay attention to. You complete your force release. And that is the system's boundary.".*

It appears that the term system is not so often used, instead terms such as components are used, but often the meaning is the same. Even though not explicitly discussed between teachers and students, the teachers agree that systems thinking is of essence. How to set up a model with the systems' boundaries, setting boundary conditions, was agreed to permeate the discipline and hence the modules in the master profile.

Teaching and Learning of Systems Thinking

Teaching and Learning Activities

One way of concretizing how the actual system differs from the model, according to teachers in the Mechatronic profile, is by way of simulating and building various systems: *"The model concept, that survives a simulation. And it…so that module is half…focused on knowledge of how to build the system. And the other half is the ability to simulate this, kind of making engineering stuff"*. Another teacher proposed laboratory exercise as an important means to teach systems thinking: *"in control technology the laboratory exercises are on a physical item. Let be it is small, but there is the computer with its software, and there is the item to be controlled. Thus, this becomes visible"*.

One teacher from the Applied Mechanics profile suggested that students' appropriation of systems thinking needs to be supported in a process of trial-and-fail/succeed: *"You might learn more from crashing and burning than if somebody tells you where to go and what to do".*

Examination

The laboratory exercises mentioned by the Mechatronics teachers also represent examination, however no explicit attention is paid to the nature of systems thinking. In the written exam in one of the basic modules (control technology) the students are sometimes asked to model a bicyclist, which reflects their systems thinking – however this task is not necessary to pass the exam as a whole. But the teacher who mentioned this found that the failure of students also reflected on the teacher: "*And, yes, many [students] get to that. But some fail. And then you* *feel totally unsuccessful as a teacher yourself".* Overall, the Mechatronics profile teachers suggested that systems thinking is implicitly examined during projects in the modules.

In the Applied Mechanics profile, the teachers agreed that no particular examination is carried out that concerns students' ability to take a systems approach to problem solving. Instead, systems thinking is considered as needed for the final major project module, and for the master thesis project. Nevertheless, a problem here is that students work in groups or pairs in these modules, and the students are not individually examined.

Progression

In line with the lack of concrete teaching and learning activities, there was also by and large a lack of deliberate and planned progression regarding systems thinking in the Mechatronics profile. However, there can be said to be a very overarching progression line between modules within the Mechanical Engineering program, concerning systems. One teacher thus pointed to the focus on hydraulic systems in the basic modules, control systems and electronics in the intermediate modules, and actual design and building of real technical systems in the advanced modules.

The teachers in the Applied Mechanics profile described in different ways how the systems understanding was built module by module: *"you start from the bottom…but during the program we simply add on to that knowledge base. In the final module, [the student] brings a back-pack with quite a few insights, and in the advanced modules you start to integrate the different things from the backpack. And kind of build the umbrella or roof over it all and thus creating greater understanding"*; and "*expand and build on, increase the complexity, make it applied, and see other applications, or more different applications"*.

The teachers are aware of this progression, but according to the teachers the students may not be. Progression also supports the understanding of present as well as past modules and knowledge: *"There are lots of equations, and they don't really understand how they are connected. And that is not strange, but simply a maturation process….On the other hand after a couple of years here, suddenly the pieces fall into place, it appears. And sometimes…when you talk to them afterwards, they don't even understand what was once so difficult"*.

The last example also connects to the next category, presented in the coming section.

Student challenges

When the teachers in the Mechatronics profile described learning difficulties among students they had mostly to do with deficient mathematics or programming skills, but sometimes also deficient knowledge of control theory or systems thinking such as the need for approximations when modelling a system. It could also be the ability to read block diagrams, or the role of flows of information in a system: *"And I have full respect that it can be difficult to get used to, as a student. But cause, effect, the relation, that is boxes and arrows.".*

The teachers in the Applied Mechanics profile also mentioned the students' propensity to get stuck in details: *"They don't see the forest for all the trees".*

DISCUSSION AND ANALYSIS

The first RQ concerns "What aspects of systems thinking are included in the Master Program in Mechanical Engineering?" This includes both the concrete systems and their elements in the respective profiles, and the more philosophical stance on systems thinking and its visibility in the profile.

For both profiles, the types of systems related closely to the topical areas and to the application areas for each profile. Based on the nature of the profiles, the Mechatronics profile included a wider scope of concrete systems, whereas the Applied Mechanics profile more focused on solid and fluid mechanical systems, with the exception of the human body as an example and also as a focus in some modules. Furthermore, static as well as dynamic systems were present in both profiles, where the Mechatronics profile to a larger extent focused on dynamic systems.

With respect to systems thinking, there was a consensus across the master profiles of the importance of integrating interacting components, and that the definition of system boundaries are all core knowledge elements in systems thinking (in line with Ingelstam, 2012; Klasander, 2010). The term model was also central although it was used somewhat differently between the profiles (cf. Hallström, 2022). In addition, a common feature between the profiles is the implicitness of systems thinking: whereas the teachers - who are also researchers - are comfortable in discussing systems thinking, they agree that this is very seldom explicitly discussed with students.

Systems thinking is often coupled with disciplinary knowledge, which supports CDIO standard 3. Furthermore, systems thinking also resonates with the CDIO emphasis on an integrated curriculum, which, in turn, promotes inter-personal skills and competencies related to the promotion of sustainability conscious engineering.

The second RQ concerns "What teaching and learning activities concerning systems thinking are included in the Master Program in Mechanical Engineering?". The question was posed openly, and the four categories of responses are a result of the discussions.

Despite prompting the issue during the interviews, only few examples were given of *teaching and learning activities* in the profiles. Laboratory exercises and trial-and-failure/success sequences were suggested to promote systems thinking among students. It appeared difficult for the teachers to define teaching activities that explicitly support the development of systems thinking among students (cf. Elsawah et al., 2022). Likewise, *examination* of systems thinking was basically not present. One example of a written task was given, but this task is not compulsory. Rather, the teachers' perception was that in advanced project courses and in the Master thesis projects, the students would probably fail without having acquired systems thinking. Hence, systems thinking is conceived to be 'implicitly examined' in relation to the overall program goals.

Progression in acquiring systems thinking was more extensively mentioned, and many examples were given. Starting with smaller components and expanding the system through interconnected components in successive modules was a pattern that arose, that would indicate progression in complexity, technical nature and size of systems. This relates to expanding the system boundaries (Hallström & Klasander, 2020), something that is also addressed in the systems thinking section above.

Besides the lack of various technical skills, an important challenge for the students over time was not to get lost in details and instead focus on the system level.

While only few examples were given of how systems thinking was taught, most of the discussions circled around topical examples which served to illustrate systems thinking in teaching, and, by implication in students' learning. Furthermore, in relation to CDIO standard 7, the teachers also function as role models: "it is important that students recognize engineering faculty as role models of professional engineers, instructing them in disciplinary knowledge, personal and interpersonal skills, product, process, and system building skills".

CONCLUSIONS

The research at hand represents the teachers' views on systems thinking in teaching in the master profiles Mechatronics and Applied Mechanics, in the Mechanical Engineering program at Linköping University. Overall, the results indicate that systems thinking is present behind the topics discussed, and also behind the development of teaching. However, more explicit discussions with students are not part of the teaching activities. Still, the teachers perceive that the students examined from the program possess a considerable capability of systems thinking. Further investigations into this topic should include the students' perspective, in order to confirm the insights gained on the basis of teachers' perspectives.

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