Educating future engineers - student perceptions of the societal linkages of innovation opportunities

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Abstract

Engineering education traditionally emphasizes technological solutions that focus heavily on students' technical skills. However, for innovations that create an impact, it is essential to link this technical knowledge to societal considerations. This paper describes a problem-centered approach towards introducing mechanical engineering students to sustainable, ethical and collaborative innovation, through an analysis of student work and feedback gathered from a ten-week long pilot conducted as part of a compulsory, Master's level, academic year-long Mechanical Engineering course.

During the pilot, student groups worked on broadly phrased challenges derived from an ongoing EU project on developing societal applications for technology, choosing one of seven challenges ranging from changing rain patterns in cities to IoT technologies and data security. Teaching was divided into three interconnected sections on sustainable development, technology and ethics, and collaboration. Each of these sections combined theory with practice through panels with experts from academia and industry and hands-on workshops, encouraging the students to consider multidimensional aspects of their chosen challenge and its consequences for the entire system it links to. A variety of design thinking methods were introduced for exploring the challenges holistically to define and reframe the problem at hand, identify ethical dilemmas and understand the needs of stakeholders for successful collaboration.

At the end of each section, students were asked to reflect on their incorporation of societal considerations to the challenge they were working on in the form of group reports. At the end of the pilot, the students presented a project proposal of a direction for solving their challenge. This paper looks at how engineering students operationalize multilayered aspects of societal issues through these reports and project proposals for 19 teams that completed both the first and last group assignment.

The results of this study suggest that introducing creative, holistic, problem-solving skills into engineering education in a hands-on manner creates numerous advantages for supporting the understanding of systemic, innovative solutions that have a societal impact and go beyond solving the technological problem. Nine sub-themes to sustainability, ethics and collaboration were identified from the deliverables; environment, economy and culture, fairness, privacy and responsibility, stakeholders, diversity and co-creation. The students' ability to identify and apply these nine measured sub-themes of sustainability, ethics, and collaboration improved statistically significantly in seven out of nine themes. The results of this study encourage linking engineering courses to societal issues through minor interventions, in order to encourage engineering students to apply a broader range of considerations in scoping innovation projects. Additionally, the coding scheme developed here can be used to gauge the level of consideration for societal issues given by students in their assignments, enabling more targeted interventions in a resource-light manner. Taken together, the results encourage iteratively developing evidence-based instruction for responsible engineering.

1 Introduction

According to UN's estimations, by the year 2050, the world's population will reach nearly 10 billion from the current 7.7 billion [1]. A majority of this 10 billion will be living in developing countries. This increase will bring great challenges for society in terms of health, climate, mobility and safety that governments will be struggling to respond to. The complexity of such challenges will require system innovations that correspond to the needs of people, profit and planet simultaneously to enable radical change. In addition to a growing population and global warming, we are facing societal challenges related to e.g. health and the digital revolution [2].

Engineering and engineers are expected to contribute towards these grand challenges [3,4]. Radical innovations that require technological novelty heavily rely on engineering knowledge [5], yet in engineering societal issues are often not given the attention they deserve [6]. Do current global norms of engineering education support students in dealing with such high levels of complexity? Are engineering students aware of societal consequences of the decisions they make? This paper focuses on how engineering students can develop a holistic understanding towards innovation, and consider sustainability, ethics and collaboration as parts of a whole in order to promote responsible engineering education through a case study from an ongoing course at Aalto University's Department of Mechanical Engineering.

1.1 Societal aspects of innovation

In today's interconnected society, innovation has gained a significant role in economic and social growth. Innovation capacity has a direct impact on the resilience of companies and regions, since it refers to the ability of finding alternative solutions and leading towards a sustainable future [7]. Being able to innovate consistently is a result of establishing a productive environment that facilitates creative awareness holistically through inspiration, realisation and education [8–10]. Innovation orientation and behaviors are also connected to entrepreneurial intent in engineering [11].

A variety of product, service or product service system innovation examples show that enabling successes that lead towards a systemic change requires acknowledging societal needs [12,13]. The relationship between society and innovation, and how they influence each other has been discussed in literature under multiple terms, such as adoption or diffusion [14,15]. All these terms refer to the impact innovation has on the existing ways of doing, making or thinking. Whether novelty is captured in a product or a service, a technological innovation requires a positive response for its target group to achieve success and sustain this status [16]. Aiming for societal change brings a whole new layer of complexity to the innovation process, since it requires constant communication between for example decision makers, engineers and the users. Narrating, communicating and receiving the positive response - the key elements of change - can be achieved through only by including these agents in the natural cycle of innovation processes. While technical achievements typically rely on engineers, engineering education curricula typically offers rather limited support to cultivating students' understanding of societal impact and can provide a limited perspective to innovation outside of dominant economic interests [17]. While there have been calls for responsible innovation [18], we have limited understanding of what engineering students' understanding of responsible innovation entails, and the impact of courses on these perceptions.

1.2 Teaching societal issues and innovation in engineering education

While implementing sustainable development into engineering curricula is not a new topic, recent years have seen an increasing number of universities across the globe to start emphasizing the need of educating future professionals who hold the ability to design holistic, sustainable, ethical and inclusive solutions to the needs of our societies. Incorporating entrepreneurship education to engineering has also been seen as a way to promote innovation and creative problem solving skills, and vice versa [11,19]. Some authors suggest that engineering students are already aware of issues concerning environmental and sustainable development, through curricular exposure especially in design project courses [20]. Others suggest it sometimes takes a little push to evoke interest and ability to consider such issues that are not central in the disciplinary discourse of one's field of studies. Watson et al. [21] suggest that increasing the expected level of incorporation of e.g. sustainability factors to the students' work might promote students to start thinking about societal issues in more detail. Attempts to measure and assess the students' abilities to implement societal considerations, such as sustainability, into their engineering projects have been made [21]. However, students seem to tend to focus on technological solution oriented aspects of sustainability at the expense of a wider range of solutions incorporating sociological aspects into their projects beyond sustainability [22,23].

Indeed, designing solutions for complex engineering challenges, holistic exploration of the problem at hand is at the core of the iterative process that requires understanding the systems that the solution is expected to influence. One approach to incorporating more human needs and collaboration driven approaches comes from the recent rise of incorporating design thinking into particularly project-based engineering design courses. In the last decade, design thinking has gained an established foothold as an approach, set of methods and mindset in a multitude of fields and industries as a human-centered way to solve complex, ill-structured problems [24]. Design thinking emphasizes understanding the problem, its context, as well as diverse stakeholders before generating ideas and a multitude of potential solutions through rounds of iterations consisting of divergent and convergent phases of ideating, prototyping and testing [24,25]. The approach should result in solutions that solve latent needs in a viable, feasible and desirable way [26,27].

While design thinking still lacks a clear definition, it has become widely used to describe a variety of designerly activities [24,28] and received some critique for maintaining the status quo of designer-centered development strategies rather necessitating co-design [29]. However, problem framing is at the core of most academic descriptions of design thinking and how it should be applied [24,30], as well as a key attribute to many engineering and technology organizations adopting design thinking practices [31]. How problems are framed guide what is considered as relevant to the issue at hand [30], and thus at a key position when attempting to understand societal issues connected to technological solutions. Design thinking can be particularly useful for responsible engineering innovation when combined with systems thinking. While design thinking may be more generative, systems thinking can be seen as a more analytical approach to problems. This kind of combined ability to think about systems rather than individual challenges paired with an empathetic understanding of different stakeholders and their needs and generating possibilities is something we see as a valuable approach to teaching societal issues and innovation in engineering education [32,33].

2 Methods

This study builds on data collected from 38 student group reports generated within the course of Mechanical Engineering in Society in Aalto University. The course is compulsory for all master's level mechanical engineering students in the university. In this paper, we focus on how the societal aspects of innovation are represented in the group assignment reports produced during the course, comparing the first and last assignments written by the students teams.

2.1 The course context

Mechanical Engineering in Society is an established course, with the aim of helping mechanical engineering students develop their professional identities as well as awareness and appreciation of how it sits with other professions, grand challenges and society at large. As such, it provided a fertile ground for running a pilot on teaching holistic problem solving. This was done through a design thinking approach and team based activities, where the emphasis lay on abilities to incorporate societal issues to given technological challenges.

The deep technology challenges were derived from an ongoing EU funded project, where nine European organizations collaborate aiming at creating an innovation ecosystem of universities, industry and European research infrastructures. The students were given seven very brief challenge descriptions to freely choose from, as well as the option to form their own challenge. The challenge descriptions were drafted by the course staff based on project descriptions from the EU funded entity. There were four main areas the challenges were on urban infrastructure, additive manufacturing, artificial intelligence, and healthcare. Two challenges were related to changing rain patterns in cities, two to additive manufacturing, two to IoT technologies and data security, and one to radiation in hospital environments. The challenges were kept as broad as possible to maximize potential scope for exploration. For example, two challenges were phrased in the following manner:

> *"The future climate predictions point towards a more frequent occurrence of severe, short and very local rain storms. These are very difficult to detect. This will have a major effect on densely populated cities, with a high level of urbanisation and infrastructure. Think about how to handle this issue BEFORE the rain storms. "*
>
> *"Additive manufacturing, 3-D printing more specifically, has opened possibilities to manufacture complex parts and shapes at a fast pace. In the context of circular economy 3-D printing can also make localization and possibilities repairing easier. Think about an industry where this can be used as an advantage."*

The pilot was divided in three main sections which aimed at covering three of the major facets connecting to societal issues that could or should have an impact on decisions taken by engineers: sustainability, ethics and collaboration. [34,35]. The learning goals for these facets included:

1. Widening the students' perspectives of sustainability and how it links to engineering.
2. Recognizing the responsibility of engineers in a wide variety of implications of technology to society.
3. Recognizing the variety of different collaborators and diverse collaboration types in creating engineering solutions.

While the sections were introduced one by one, the overall workshops and deliverables required the students to build knowledge towards a final project-proposal that should incorporate their learnings and where they should present the aspects of these issues that should be taken into account when going about solving their chosen challenge or that would have an effect on the project.

Each section followed a three-fold structure that consisted of a seminar, workshop and finally, deliverables. The structure was planned to maximise students' interaction with the topic and to be able to provide opportunities for multilayered interpretations. Timing-wise, the course was set in three week long cycles per section. In the first week of each cycle, the seminar part of the section took place, in the second week of the cycle there were the workshops, and the third week was designated for preparing the deliverables. The pilot was mainly conducted by an interdisciplinary teaching team of three. However, the seminars required the contribution of invited speakers and the workshops had visiting teaching staff to either introduce the topic or to help in facilitating the group work. The team had previous experience from teaching design, engineering design, entrepreneurship and communication.

Seminars:
Each section was first introduced by a series of keynote speeches from industry and academia speakers, which allowed the students to get acquainted with multiple aspects of the topic at hand. During the seminars, the students heard first-hand perspectives and expertise and were able to engage in section-specific discussions before reflecting this knowledge on their chosen challenge.

Workshops:
The pilot included three two-hour workshops that focused on different aspects of potential societal linkages of the student teams chosen engineering challenges. The three workshops had a preceding seminar as stated before, students working in the same team of three to six students through the course. The workshops were designed in a way to let the students think outside the box in relation to the subject of the section. To facilitate this a variety of design and systems-thinking originating methods were used, such as PESTEL-analysis, reverse brainstorming, entangle method and stakeholder mapping [36–38].

To give an example, during the first workshop the students formed teams and decided on a challenge, after which the teams gathered information on political, economic, social, technological, environmental, and legal issues related to their challenge. After gathering the information, they moved on to defining their challenge and solution direction, finally drafting a vision statement for their challenge.

Deliverables:
Student groups were expected to deliver a series of short reports, in which they discussed the insights gained through the seminars, building on the work started in the workshops as well as reported their findings, progress and further insights. Deliverables enabled the students to articulate their insights and structure the fragmented knowledge accumulated throughout the course. In this paper, deliverables are considered as the main tangible outcome of the course at hand, therefore, students' ability to incorporate societal linkages to engineering problems are traced through these deliverables.

Four interdependent assignments were given to the student groups in this course. In the first assignment, given at the end of the first workshop right after the introduction of their project challenges, the student groups were asked to describe their challenge in the way they interpret it and formulate a vision statement based on their interpretations. They were also asked to include the opportunities, strengths, risks and challenges regarding sustainability that they see that were linked to their challenge based on the first seminar and workshop. The recommended length for this first report was 3-4 pages.

The second assignment included reporting the insight gained during the workshop and discussing ethical dilemmas the team had identified as well as tradeoffs of engineering decisions made regarding the identified dilemmas. They were also asked to create and elaborate ways to overcome those ethical dilemmas as well as ways to utilize potential opportunities for development.

The third assignment was given after the collaboration themed workshop, thus the students were asked to discuss their skills and knowledge, gaps they could identify in their skills and knowledge as well as the key stakeholders regarding their chosen challenge and ways to include, as well as goals of including these stakeholders to their project plan.

The final deliverable was due after a final workshop where focus was on communicating the teams insights and findings in a compelling and clear way. The students were given more freedom in the form they complete the final assignment, asked to do an informative and appealing two-page project proposal, based on their previous work, for a project that aims at overcoming the challenge the group had chosen. All of the teams chose to write reports while some included more visual elements than in the previous deliverables.

2.2 Data collection

The analyzed data in this study is a part of the course deliverables that were handed in, in the form of reports at the end of each section by student groups. The report lengths vary from two to four pages depending on assignment. The students were given a guideline of producing approximately four pages long reports for the first three assignments on sustainability, ethics and collaboration, and a two-page project proposal as their final report. This study builds on the first and last submitted assignments focusing on the vision the teams have in the beginning of the pilot as well at the end of the pilot.

The first assignment was submitted by 22 groups, and 21 teams submitted a final project proposal. Three of the groups had to be ruled out of the analyzed data set, as they were lacking either their first report with a vision statement or their final report that was the project proposal. The first and last assignment deadlines had eight weeks between them. Therefore this data set consists of 38 reports submitted by 19 student teams of three to six students. Altogether the sample represents 93 students from the master's programme in mechanical engineering, with an average student team size of 4.9.

2.3 Data analysis

Thematic analysis

In this paper, we have closely examined the course deliverables to explore common topics, ideas of meaning that come up repeatedly. The nine emerging themes that were used for the thematic analysis derived from the course content explored throughout the sections. Within these themes, patterns were studied using thematic analysis, a process of identifying patterns within qualitative data by breaking down the bits of information into themes [39] and a quantified comparison of distributions between rankings of issues in the first and final deliverable.

As the course was structured into three sections (sustainability, ethics and collaboration) emerging themes within course content and deliverables were identified separately for each of these sections. For the sustainability section, the themes followed the three main elements of Elkington's Triple Bottom Line model, that are originally identified as people, planet, profit [40]. These three concepts are adapted into the course as the **environment, economy** and **culture** themes that reflect the sustainability section.

The second section of the course focused on ethics. Ethics emphasizes the professional codes that enable the fair development of technology that respects the rights of living organisms as a whole. Involving ethics into engineering education directs the students towards moral commitments and gives meaning to their work, which is aimed at benefiting public good but eventually enables self-fulfillment as well [41]. The themes that we have looked at under the ethics section derive from the four pillars of ethics in technology that are commonly known as fairness, robustness, privacy and explainability [42]. These also correspond to the topics that have been covered during the workshops and keynote speeches, reframed into three themes of **fairness**, **privacy** and **responsibility** (encompassing both robustness and explainability).

The third and the final section of the course focused on the necessary diversity that has to be recognized in terms of completing the skillset of the teams, how they function together and the collaboration with internal and external actors. The importance of stakeholders' role in sustainability is widely recognized [43], and during the collaboration section, the student groups operationalized this by broadening their **stakeholder** mapping towards the **diversity** of existing skills within and around their team and discussed the necessity of **co-creation** to achieve greater systemic impact. These formed the three coding themes for collaboration.

To summarize, the nine themes that were used in the coding and analysis of the data is listed as follows:

1. Sustainability: Environment, Culture, Economy
2. Ethics: Fairness, Privacy, Responsibility
3. Collaboration: Diversity, Co-creation, Stakeholders

To measure how these nine themes were incorporated into the student groups' reports, we have used a five-point scale system as a representation of groups' semantic distance towards these nine themes. Semantic distance refers to commonality of meaning between two or more different forms, and is a widely used term in cognitive psychology and linguistics [44,45]. This semantic distance scale, explained below, helped us to identify how deep student groups' had elaborated on the nine predefined themes in their reports.

No mention of the theme	0
Indirectly referred to the theme	1
Briefly mentioned the theme	2
Wrote a few sentences on this theme	3
Discussed the theme and its implications	4
Incorporated this theme in their solution proposal	5

Statistical analysis

The coded categories were then analyzed statistically to assess the significance of differences in the students' embedding of societal concerns between their first and their last report. The analysis was carried out separately for each of the nine themes.

As the data failed normality tests, distribution-free statistical methods were used to analyze the significance of the results when comparing the semantic distances of student groups to the defined themes in their first reports (vision statement) to their last reports (final proposal). The coded ranks for all 19 student groups (A to V) for each of the nine themes, both in vision statements and final proposals, can be found in the Appendix.

A two-tailed Mann-Whitney U-test was used to assess the significance of the differences between first and last submission of the total number of student groups. The resulting p-values were considered statistically significant if they were smaller than .01. For seven of the nine themes, the difference was significant enough to be considered meaningful (p value varying between 0.0001 - 0.00758). Changes in two of the nine categories were not significant (p value varying between 0.4295 - 0.7565). When correcting for multiple comparisons using the Bonferroni method (p value threshold divided by the number of comparisons made, i.e. 0.05/9=0.0056), five increases remained statistically significant. The potential reasoning behind these results are discussed in the following section.

3 Results - How engineering students perceive societal implications of innovation opportunities?

Comparing the societal considerations around sustainability, ethics and collaboration in the innovation problem statements and final project proposals 19 engineering student groups, we found some systematic differences in how these facets were included in the written reports of the students. Looking at the change between the first and last deliverable, it is possible to identify a positive change in terms of semantic distance towards sustainability concepts. As seen in Figure 1, the overall rise of the semantic distance rankings suggest that the students have broadened their perspective towards societal issues throughout the course. Additionally, the students' discussions on diverse concerns gained depth throughout the course. In all categories combined, the first reports had an average semantic distance rank of 1.36, underlining the low levels of embeddedness of societal concepts in general, whereas the final reports had an average semantic distance rank of 2.62, representing a statistically significant increase ($p < 0.0001$).

For the majority of the groups, sustainability related concerns ranked higher (i.e. where discussed more frequently and to a further extent in the reports) than ethics and collaboration-related concerns. This could be related to the students' pre-existing concerns or to the knowledge they have obtained in other courses they have taken before. The exercises the student groups picked could also have an influence on their semantic distance to some of the concerns, causing higher starting ranks in some of the first reports. For example, a group working on data security was naturally concerned about privacy from the beginning, even before the Ethics section took place. In these cases, one must look at the development of how the groups' semantic distance has evolved for other subjects, rather than compare across student groups.

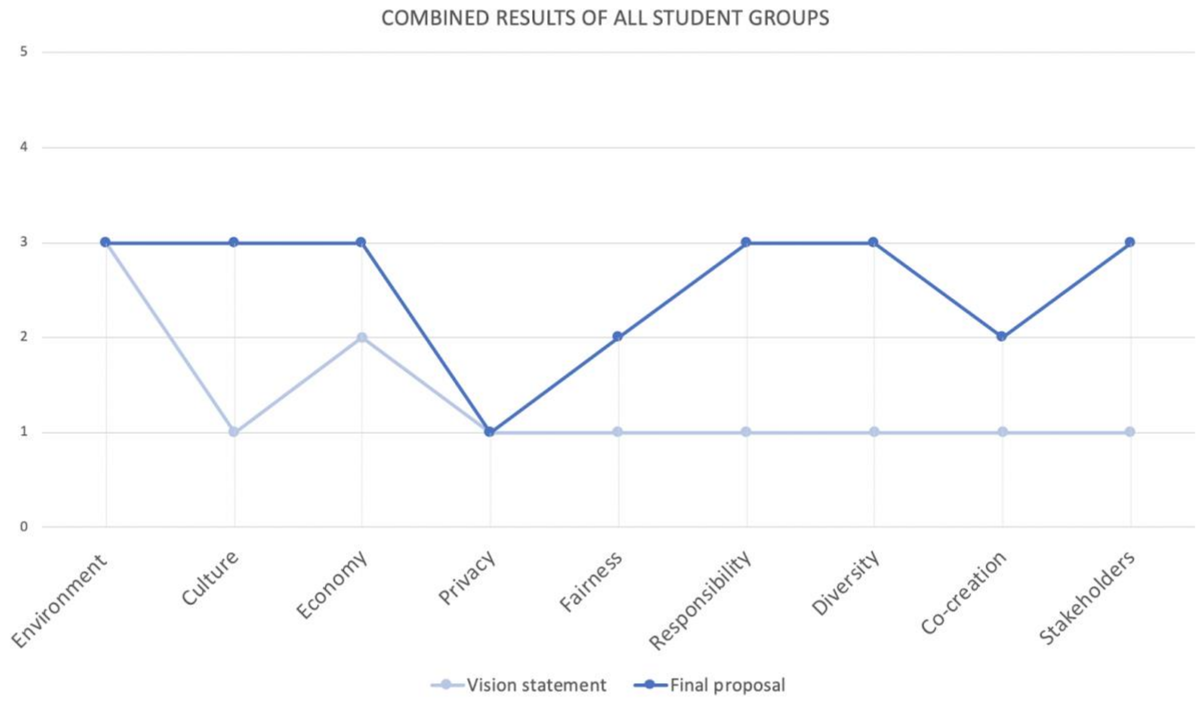

Figure 1. Development of students' semantic distance rankings throughout the course regarding the nine identified themes

Figure 1 shows an overview of the development of students' semantic distance of the nine themes. The light colored line shows the average score received in the vision statement reports on each theme, while the dark colored line shows the average score received in the final proposals on each theme. On seven of the nine themes, the lines indicate a clear improvement in students' semantic distance. The two themes that did not present improvement were the environment theme in the Sustainability cluster, and privacy theme in the Ethics cluster. The content and meaning of each theme, the reasoning behind the increase of the 7 themes and the argumentation behind the lack of improvement in two themes are next discussed under designated sub-chapters.

3.1 Sustainability

Environmental concerns

The era that we live in requires each and every individual to adopt ecological consciousness as a mind-set and therefore, this is one of the most important subjects when making students aware of the potential linkages of engineering decisions and society. The topics that fall in this category of concerns are sparing use of resources, circularity, obting for natural materials and re-use and repair of existing products or parts.

Thematic analysis of the student's reports showed that all of the 19 groups mentioned environmental concerns in both their first report (vision statement) and their final report (proposal). When we compared the environmental concerns that were discussed in the first deliverable to last deliverable of student groups, their semantic distance scores remained relatively high as seen in Figure 2. Only 9 out of 19 student groups had any increase in their understanding of environmental concerns as reflected in the rankings, and it tended to be small. For example, one of the student reports mention plastic waste and carbon dioxide missions without incorporating it into their solution proposal:

“At the same time the climate is warming due to CO2 emissions, plastic garbage patch, Pacific trash vortex, spans waters from the West Coast of North America to Japan. Are we drowning in plastic waste and CO2 emissions due to 3D printing?” (group C, final report)

Five groups out of 19 maintained their semantic distance towards environmental concerns throughout the course, and the remaining 5 student groups (A, B, C, P, Q) portrayed a slight decrease in their incorporation of environmental concerns when we compare the two deliverables. The change in environmental concerns was not statistically significant ($p = 0.42$, U-value is 153, the critical value of U at $p < .05$ is 113). However, the reports also showed a shift towards other directions in the students’ ecological concerns, as more themes were introduced throughout the course.

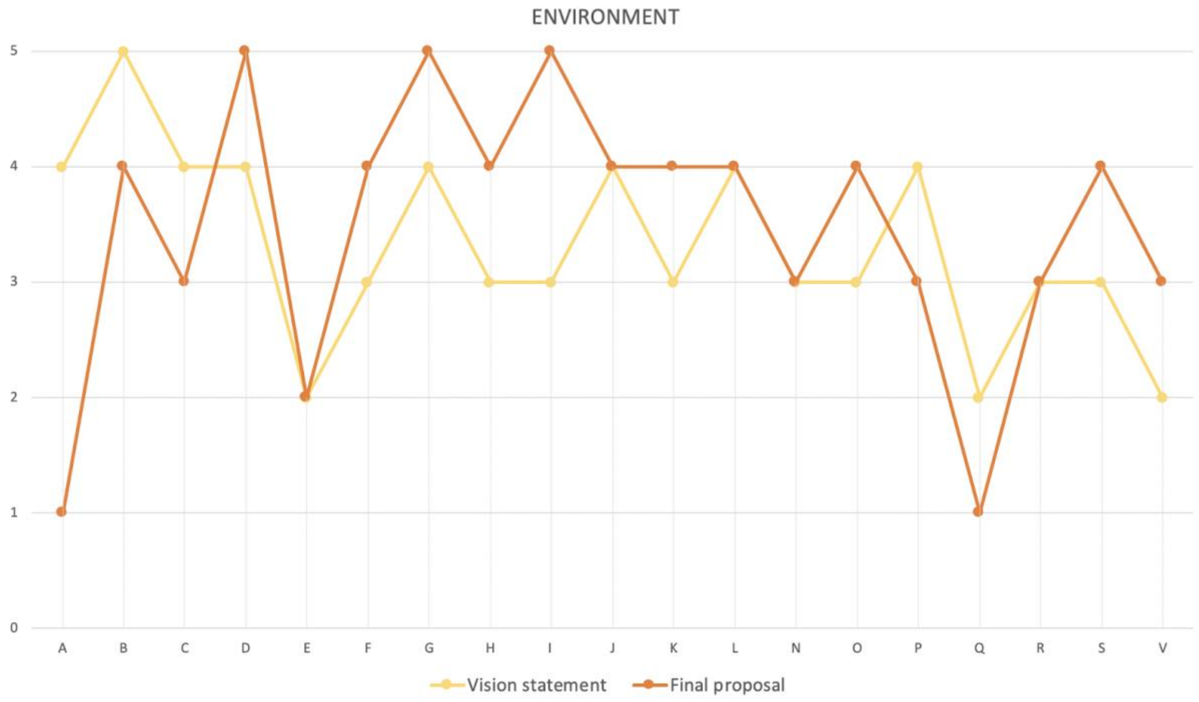

Figure 2. Development of semantic distance rankings for all 19 groups for the ‘environment’ theme

<u>Cultural concerns</u>

Cultural concerns that students raised in their reports related to the prosperous development of society that the innovation would be introduced to, evolving hand-in-hand with the technological advancements. The topics that fall into this category are changes that are implied on human life, new ways of communicating between individuals, as well as changing work-cultures in business settings. For example, one of the groups considered the impact of autonomous vehicles on taxi drivers:

“The biggest prey in the job market that autonomous vehicles have are taxi drivers. In a city with autonomous vehicles that are able to drive people up and down the city while the owners are working, for example, would highly decrease the demand for taxies, especially when you do not need to pay the taxi driver’s salary.” (group D, first report)

Five groups did not consider cultural aspects at all in their vision statements (semantic distance rank = 0), and another 5 only indirectly mentioned it (semantic distance rank = 1). However, in their final proposals, the majority of the groups gave more depth to their linking of cultural concerns (16/19). For example, in their final report, one group exceeded the boundaries of the given engineering problem, and discussed the issue on a meta-level by reflecting on the systemic impact of their potential solution that leads towards citizen empowerment. The group quotes on the importance of education for women in the context of a developing country, and therefore underlines the necessity of changing the mindset as follows:

> *"An important contributor to this is education, especially for women. With education comes the realization that things could be better and that "I can make a change. Living passively, settling for the current situation, does not lead to improvement."* (group Q, final report)

This increase in consideration was statistically significant at *p*=0.0057 (U-value is 85.5, the critical value of U at $p < .05$ is 113). Still, one must realize that in many of the groups (10/19), the ranking only changed by 1 point, which underlines the difficulty of embedding cultural concerns in engineering decisions, even after attending seminars and workshops that specifically tackle this topic.

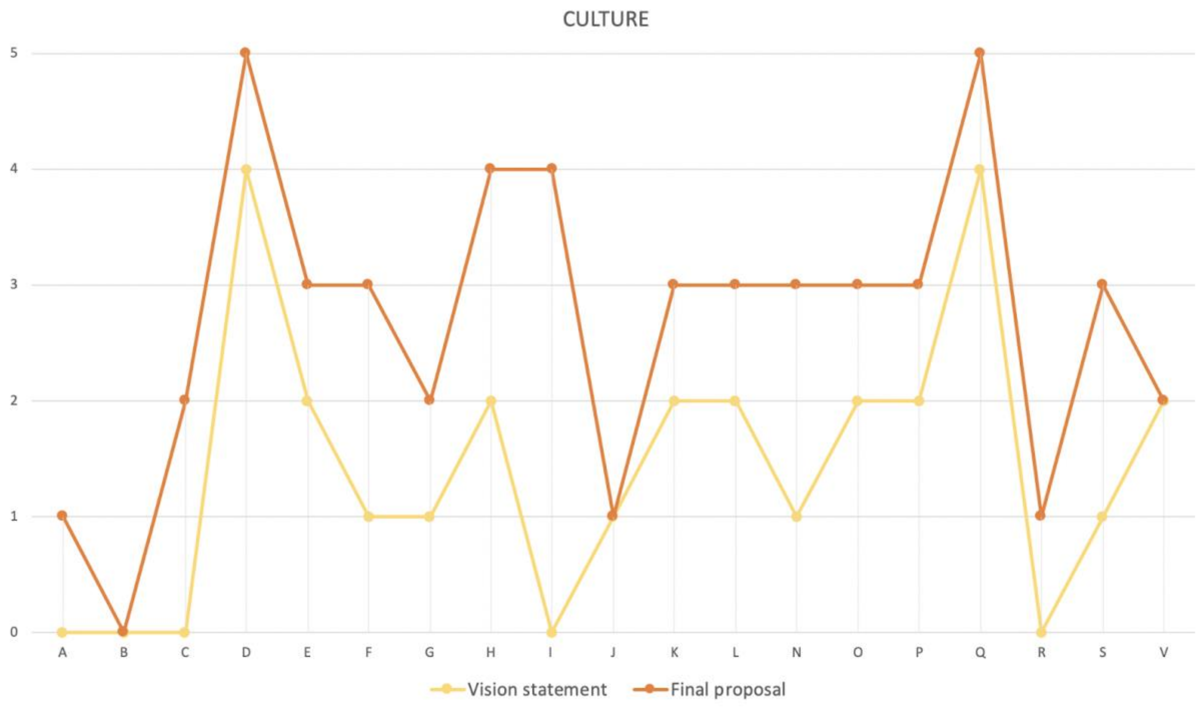

Figure 3. Development of semantic distance rankings for all 19 groups for the 'culture' theme

Economical concerns

Economical concerns relate to the profit making potential of innovations that heavily relies on engineering decisions but at the same time evolves in harmony with environmental and cultural concerns in order to sustain a comfortable lifestyle for citizens while enabling further technological advancements. The topics that fall into this category are alternative business models, economies of disadvantaged groups or areas and providing certain services or products for less. For example, one of the student reports mentioned business opportunities and the need of international standards to pursue them:

> *"The IoT plays a key role in sustainable cities and communities. Successful and safe IoT technology will create more career and business opportunities. Our research shows that the most effective, and maybe also only global, solution for data security issues are laws, standards and contracts."* (group E, first report)

All student groups were concerned about the economy in some manner in the initial reports. Some took it from a global point of view, where the purpose is to invest in the development of those who are in need, while others pointed out alternative techniques that could not only be environmentally friendly but also profitable. From the 19 groups, there was only one group that reflected on the economical benefits of their particular initial solution (semantic distance rank = 4). Another group mentioned profit in their vision statement, but reframed their focus in the final proposal in a way that does not raise economical concerns (group D). In general, profitably was mentioned or discussed as an issue in the beginning and at the end, but not a main concern portrayed in the reports., as shown for example in the following brief mention of profit in one of the final reports:

> *"Big corporations do not often think about nature, only large profits and therefore, it is a business opportunity to be a responsible company."* (group R, final report)

The increase of the students' reflection on the economy was statistically significant (p = 0.00758, U-value is 88.5, the critical value of U at $p < .05$ is 113).

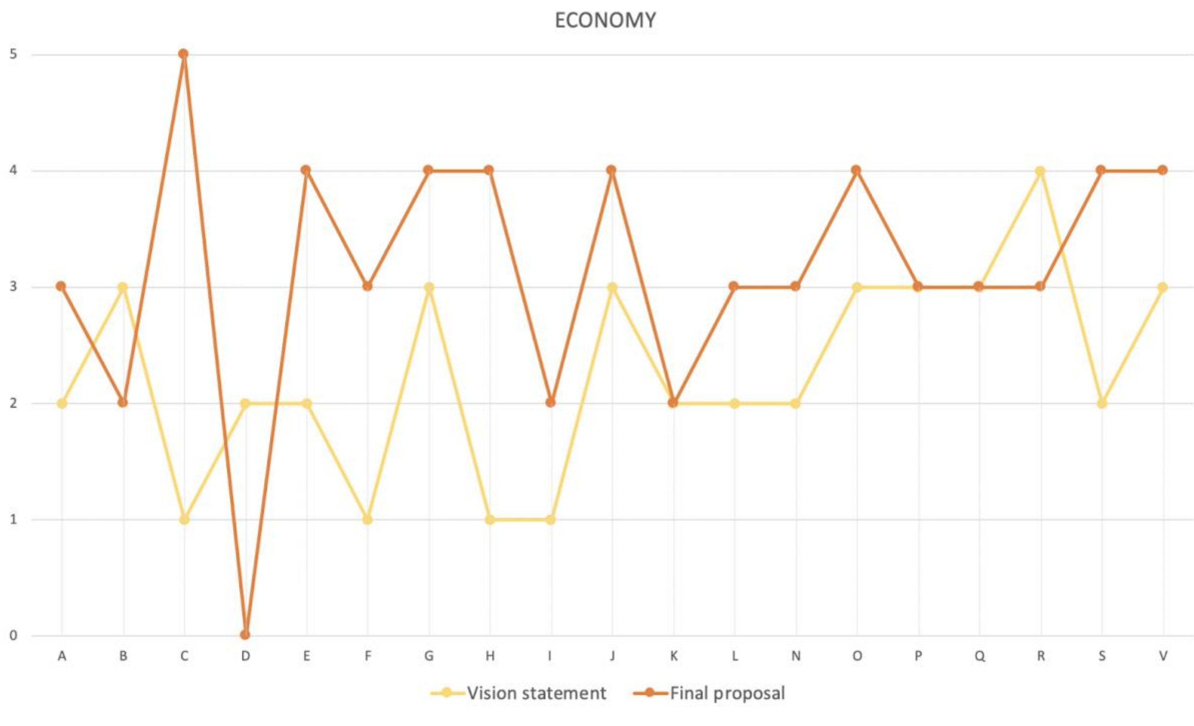

Figure 4. Development of semantic distance rankings for all 19 groups for the 'economy' theme

3.2 Ethics

Privacy concerns

As societies are getting more and more connected through new channels that even become a part of households, privacy becomes increasingly important for safety and comfort of individuals [46]. Under the Ethics section, potential risks that are not necessarily recognized yet were identified and discussed. Students argued a variety of issues regarding privacy that include, but are not limited to, the potential attacks on AI-based products, privacy of individuals at home and at the workplace, protection of intellectual property rights, as well as data security when dealing with big data.

Privacy was one of the two themes where the change in consideration was non-significant (p=0.75, U-value is 169.5, the critical value of U at $p < .05$ is 113). As seen in Figure 5, a majority of the student groups did not raise concerns towards privacy neither in their first nor last report (13 out of 19 groups). On the other hand, one group (E) raised privacy and hacking-related concerns related to the safety of individuals, in both analyzed deliverables, dealing with a digital security challenge. This group deeply elaborated on privacy concerns already in their first report and used the privacy aspect as a starting point for ideating solutions for their challenge:

> *"It is important to find a solution for our challenge as IoT devices are getting more common everyday and it is very likely that soon everyone is an IoT user. Because of this privacy will be an issue, since IoT is important as it guarantees equality and freedom. If IoT devices are not secured, soon everyone will have spying devices at home and the data these devices collect can be used against their users."* (group E, first report)

A further four groups (L, N, R, S) increasingly raised privacy concerns. Their reports clearly indicate the realisation of the importance of the privacy matter through the exercises they have done in the workshops, discussions with experts during seminars and their explorations. For example, one of the groups that incorporated privacy discussions in their solution proposals noted that:

> *"Another legislative matter is the digital intellectual property rights regarding the 3D-printed products... There needs to be strong disentives against piratism and intellectual property theft. This can be solved by making the designs of the products or parts to be printed cheap and easily available for everyone. The incentives for piratism can also be reduced by enforced laws, with better intellectual property laws"* (group L, final report)

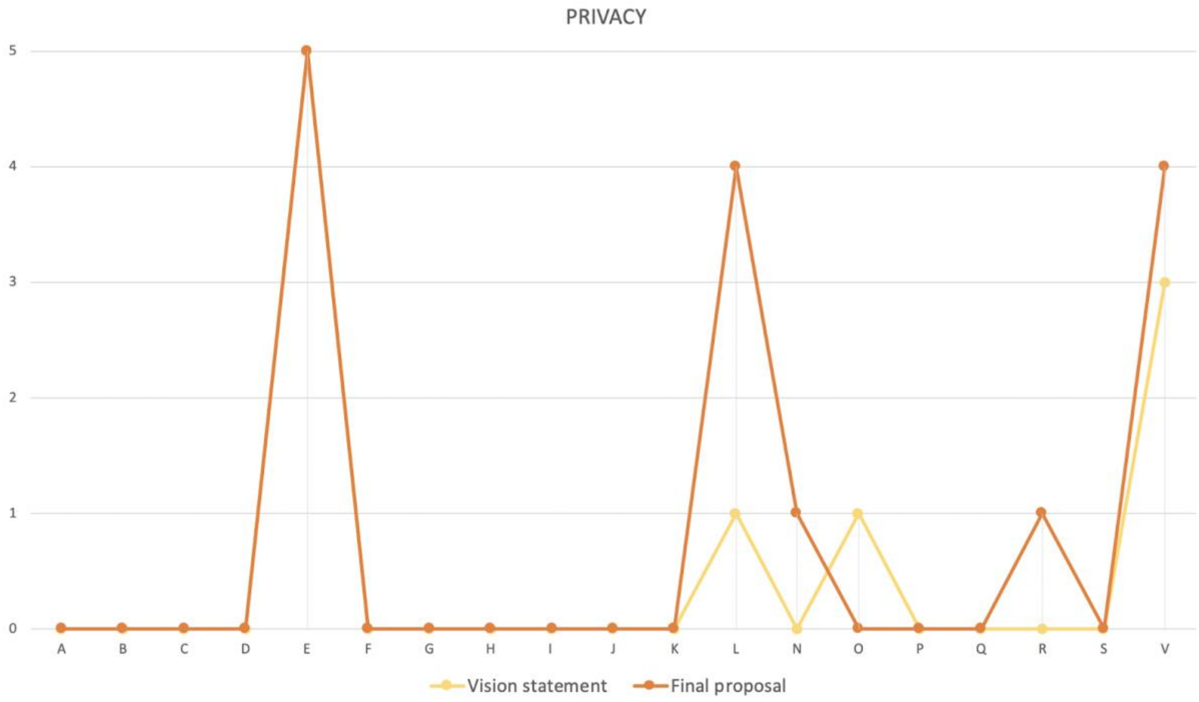

Figure 5. Development of semantic distance rankings for all 19 groups for the 'privacy' theme

Fairness concerns

Fairness aspect refers to the quality of progress without isolating a part of society or the planet from the other. Technology is expected to work in the benefit of common good, and therefore engineers must make decisions without causing disadvantageous situations. However, fairness is a complex phenomenon, especially in business context, as actors in multi-stakeholder processes have different expectations [47]. During the course, the student groups were asked to reflect on the potential unfairness that their challenge and/or solution proposal might cause directly or indirectly. For example, one group reflected on the accessibility of 3D printing due to its relative cost:

> "*Completely another issue of 3D printing is inequality of the machinery. Even though 3D printers are affordable to most of us, for example in Africa, the person who owns the only printer of the village would quickly obtain a dominant position of producing goods. This would cause wealth to stach [sic] to just 3D printer owners, and wealth made by printers would not benefit all members of the society."* (group O, first report)

However, as seen in Figure 6, students were mostly not concerned about fairness in their vision statement, which was written before the introduction of the sections. Eight out of 19 groups did not mention fairness in their vision statement, and another 9 only indirectly referred to this theme. In the final proposals, many groups discussed the potential misuse of their ideas in a variety of contexts. 18 out of 19 groups mentioned fairness, even if indirectly:

> *"Our goal is to follow and emphasize sustainability, equal payment for employees, gender equality and respect for regulations. By following these values, we see ourselves as a company with good will and ambition to create a better industrial service worldwide than ever before."* (group H, final report)

The average semantic distance ranking went to 2 from 0.73 demonstrating an increase that was statistically significant even when correcting for multiple comparisons (*p*=0.00078, U-value is 65, the critical value of U at $p < .05$ is 113).

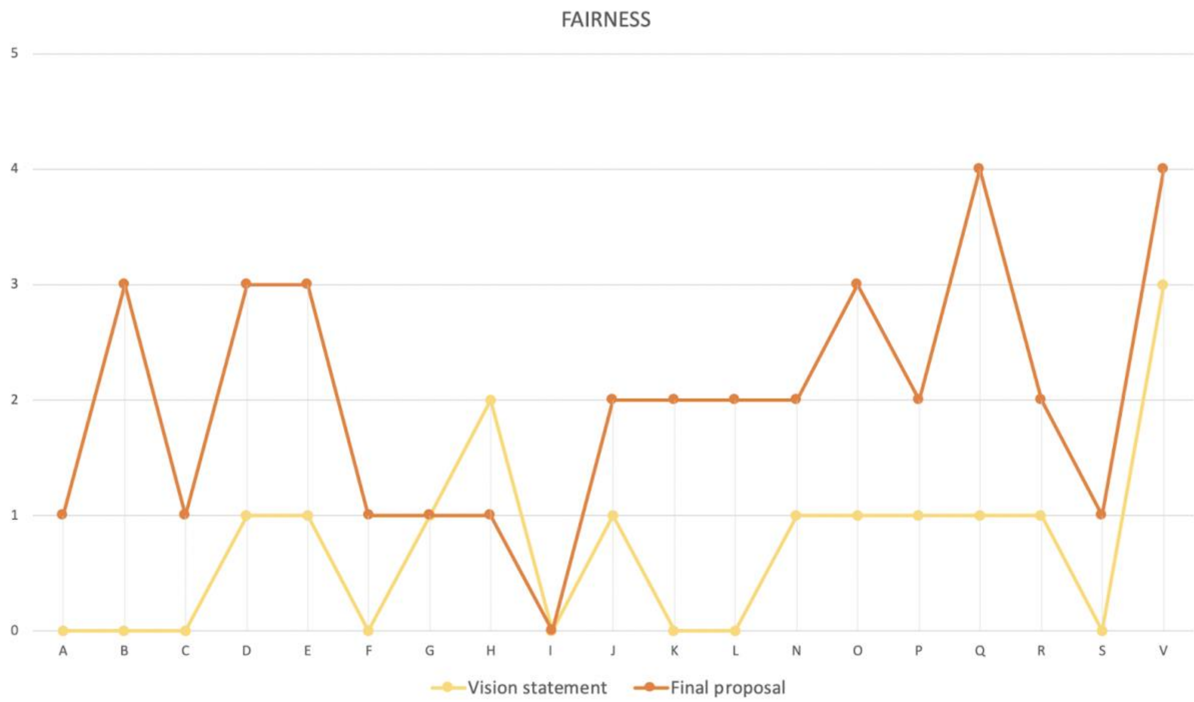

Figure 6. Development of semantic distance rankings for all 19 groups for the 'fairness' theme

<u>Responsibility concerns</u>

Responsibility refers to caring about the wellbeing of living mechanisms and the systems that support their harmonious development. Technological innovations that enable the materialistic development of humanity, evergrowingly requires engineers to question the necessity of their actions [48]. As a part of the Ethics sections, the students in the course discussed responsible innovation in terms of safe and lawful interventions, as well as corporate responsibility. For example, one group reflected on safety in autonomous vehicles:

> *"Our objectives include more high-tech and safer AI networks in self-driven cars keeping human safety and efficiency factors in mind. Theoretically, AI is able to re-perform everything that humans are capable of, meanwhile, the error of unexpected behaviour of machines is so much less than humans."* (group D, final report)

Figure 7 shows that the students started the course with a low demonstration of responsibility consideration. A majority of the groups only indirectly referred to potential risks or damage the solutions to their challenge could create (semantic distance rank = 1 with 12/19). Six groups exceeded this by writing at least a couple of sentences on the aims to achieve responsible innovations. One group did not mention this theme at all in the first report.

In their final proposals, all the 19 groups have at least mentioned responsibility. The average semantic distance rank increased to 3.5 in the final reports from 1.4 in the vision statement, representing a statistically significant increase even when correcting for multiple comparisons ($p < 0.00001$, U-value is 23.5, the critical value of U at $p < .05$ is 113). Within these, there were

15 groups that increased their semantic distance rank by at least two points. For example, one group went from indirectly referring to responsibility to reflecting on issues of responsibility in 3D printing, citing examples and considering how to guard against misuse:

> *"Before widespread consumer use of 3D-printing, there are some things that need to be considered. First, the potential risk of dangerous products like guns being produced is a major concern. Since designs for products are transferred digitally, the trace can be hidden quite efficiently. Even though it can be hard, there still needs to be a strong legislative movement towards protecting against potential misuse of the technology."* (group L, final report)

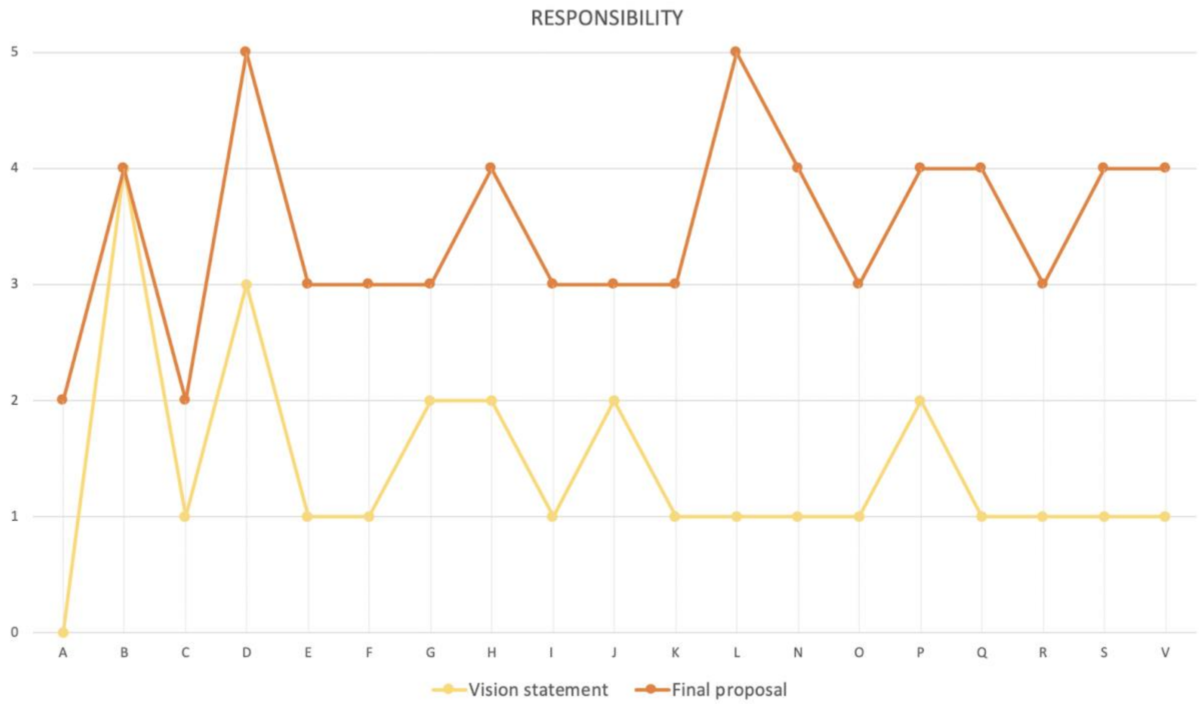

Figure 7. Development of semantic distance rankings for all 19 groups for the 'responsibility' theme

3.3 Collaboration

<u>Diversity concerns</u>

The diversity theme refers to the inclusion of multiple perspectives when solving engineering problems. In the world of management team diversity in terms of skills is commonly accepted as a beneficial aspect, and diversity brings advantages to a company's ability to innovate. But when it comes to practice, engineering teams commonly prefer technical knowledge that is readily available within the existing team [49]. As a part of the theme, the students traced the diversity of their skill-set within the team as well as identified the missing elements in order to achieve their goals. It is important to mention that we observed a significant improvement in this category after a skill-mapping exercise that was done during the third workshop.

Figure 8 shows that 15 of our 19 groups initially indirectly referred to the necessity of diversity when solving their challenge. As the groups were dealing with complex societal problems, it was clear to the students that new skill sets are necessary. For example, one group quotes on the necessity of multidisciplinary collaboration as follows:

> *"Collaboration with lawyers, business professionals and component suppliers must also be considered in this stage."* (group A, final report)

The average semantic distance rank went from 1.15 to 2.73 in the final reports, representing a statistically significant increase even when correcting for multiple comparisons ($p < 0.00001$, U-value is 36, the critical value of U at $p < .05$ is 113).

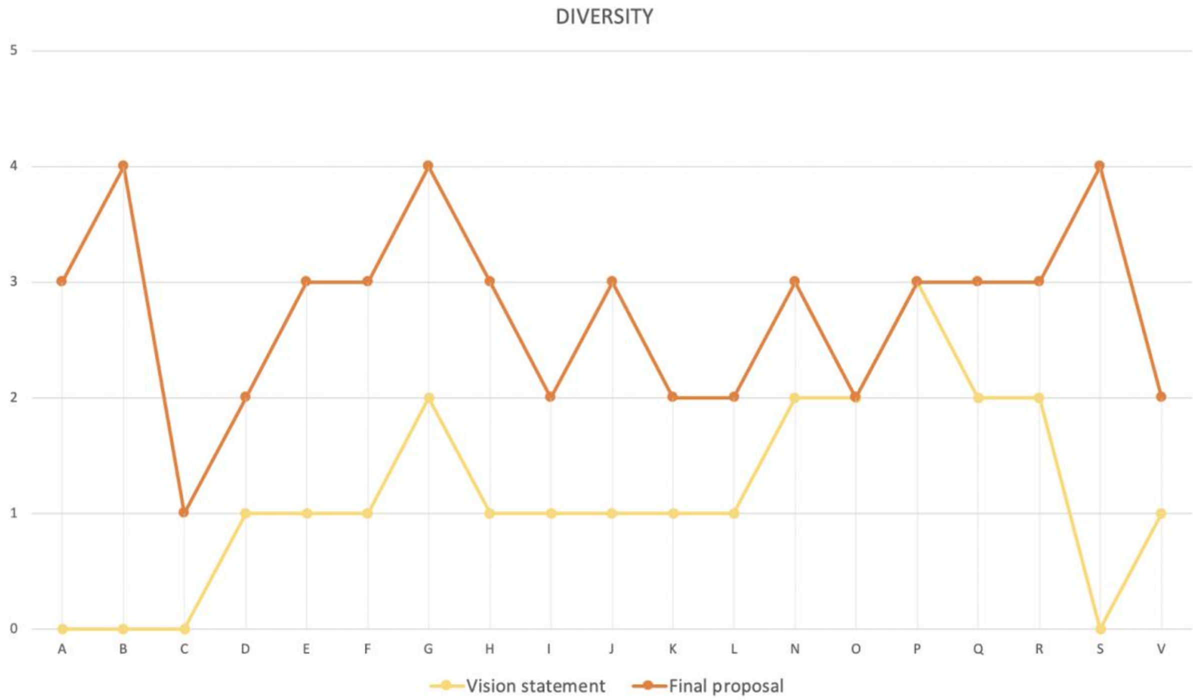

Figure 8. Development of semantic distance rankings for all 19 groups for the 'diversity' theme

<u>Co-creation concerns</u>

The proliferated term of co-creation refers to the practice of value creation as a collaborative activity that design and business scholars have been underlining for decades [50]. Co-creation aims to involve a variety of stakeholders in the process of finding solutions in order to achieve relevant results for the end-users. For example, some reports identified potential collaborators with whom to develop their solution further, both from the supplier and application sides:

> *"Collaboration with other eco-minded businesses and projects, would be highly beneficial and desirable. As 3D printing as a manufacturing method is still developing, we also have to keep adapting to new ideas and solutions from collaborators."* (group K, final report)

> *"The team relies heavily on a strong 3-way communication system between healthcare professionals, customers and the team. In this proposed business model the patients are considered to be the customers, or more accurately the users, the*

team is the "contractor/supplier" and the healthcare professionals act as specialist consultants to the team" (group A, final report)

Co-creation had one of the lowest semantic distance ranks in the vision statement reports, with only two of the 19 teams even indirectly referring to it. However, throughout the course, as the complexity of the assignments were acknowledged, and the missing knowledge became apparent, co-creation considerations increased. In the final proposal, almost the entire class mentioned the necessity of co-creation for the potential solution (17/19), from which 4 groups discussed co-creation opportunities (semantic distance rank = 4). The average rank increased to 2.3, which was statistically significant even when correcting for multiple comparisons ($p < 0.00001$, U-value is 23, the critical value of U at $p < .05$ is 113).

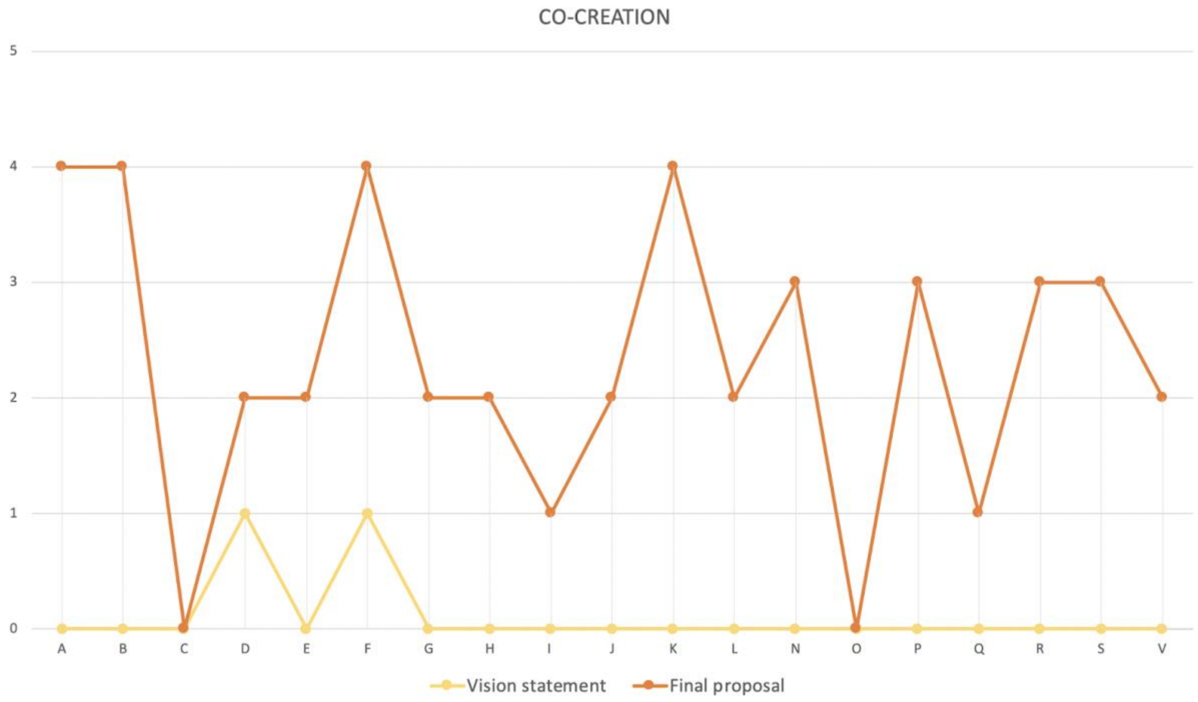

Figure 9. Development of semantic distance rankings for all 19 groups for the 'co-creation' theme

Stakeholder concerns

Last but not least, the final theme of the Collaboration section focused on the communication with the stakeholders that are or should be involved in the process and that are affected by the results. The students were expected to acknowledge the relevance of different types of stakeholders in their journey towards an impactful solution and identify their level of involvement in the decision making process.

Unlike the other themes of this section, student groups had a relatively high awareness of at least some stakeholders to their project from the start. Fourteen out of 19 groups mentioned the relevance of involving or informing stakeholders in their vision statement, even if sometimes indirectly.

> *"The stakeholders are essential since they are aware of the consequences described above, are in leading positions amid health care professionals, and are involved in the development and enforcement of current safety measures."* (group B, final report)

However, Figure 10 illustrates that together with the diversity and co-creation themes, it became growingly evident for teams that involving stakeholders would be beneficial for their project. The semantic distance rank grew to 3 from 1.3, a statistically significant increase even when correcting for multiple comparisons ($p = 0.00038$, U-value is 58, the critical value of U at $p < .05$ is 113).

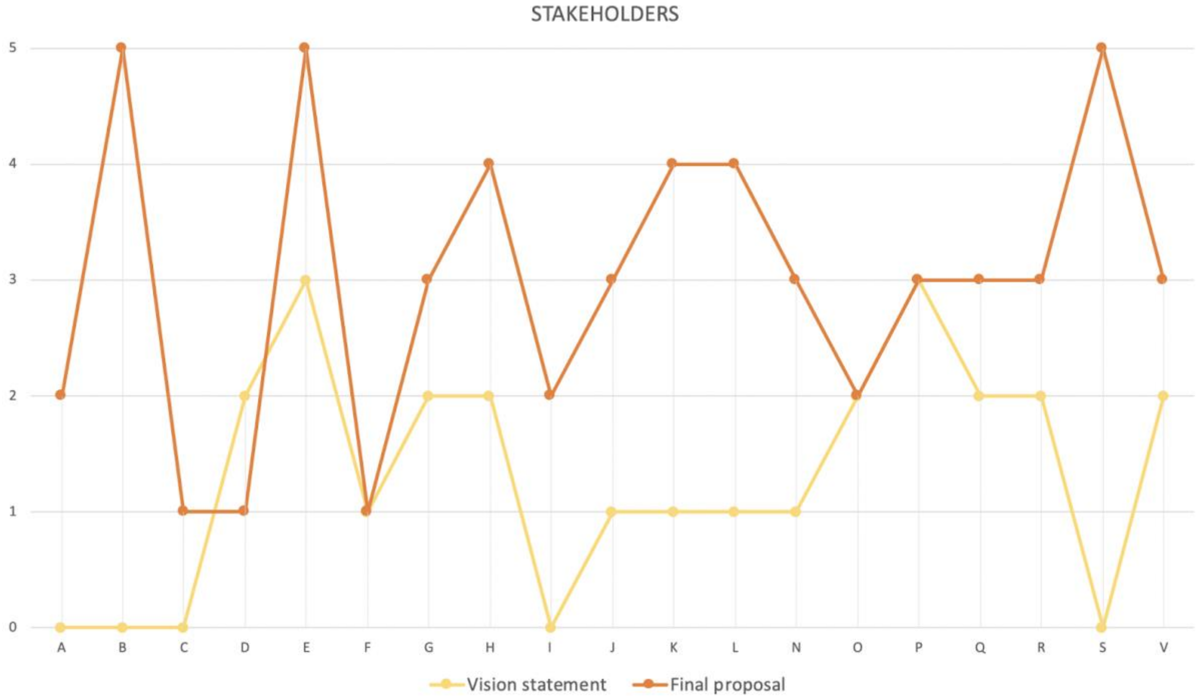

Figure 10. Development of semantic distance rankings for all 19 groups for the 'stakeholders' theme

4 Discussion

This paper describes a study of investigating engineering students' perceptions of societal considerations in relation to innovation opportunities in certain technological challenges. Student teams' report deliverables were analyzed to find out how engineering students perceive societal implications and understand how they link to their challenges and innovation opportunities. The students were taught and guided to use creative problem solving approaches and methods often linked to design thinking in a series of panel discussions, workshops and assignments. Previous research has demonstrated that better learning outcomes of sustainability related challenges are reached when multi-method learning experiences are produced [20]. Additionally, problem-based design challenges and teaching have been connected to increase awareness of societal issues, entrepreneurial intentions and innovation self-efficacy amongst engineering students [11,20,51], highlighting the benefits of generatively applying knowledge within courses. Overall, the students ability to implement the measured sub-themes of sustainability, ethics and collaboration in seven out of the nine sub themes improved statistically significantly. Only two subcategories did not improve across the reports: *privacy* (scarce in most reports) and *environment* (typically represented well in all reports from the start).

Engineering students conventionally focus on targeted technological advancements in their project assignments during their education. Societal implications of such advancements are seldom discussed. For example, Leydens and Lucena [52] present several cases where engineering students are simply not interested in societal dimensions of technical knowledge. The authors search for the origins of this prejudicial issue in the early years of education, where students are thought to believe that those that are good at mathematics would succeed in engineering education. Leydens and Lucena [52] suggest that as a result, students prefer to excel only in what they are already good at, and refrain from dealing with societal issues that are conventionally not included in the category of technical studies. However, a number of engineering programs have sought to introduce socially responsible innovation to their curricula to widen the capabilities of engineering and enhance their ability to advance social, environmental and economical issues [e.g. 53–55].

The current study offers encouraging results as a fairly minor intervention was able to yield at least temporary increases in the sustainability, ethics and collaboration considerations of engineering students in innovation project proposals. Furthermore, environmental issues were at a relatively high level even in the first round of reports (although this might have been influenced by having the deliverable deadline only after the first section). It may be that general media coverage has increased awareness towards ecological issues, as students are surrounded by discussion regarding climate change, pollution and energy consumption that cover (social) media on a daily basis. In addition, many engineering courses do already incorporate some sustainability considerations, although typically focusing on technological rather than sociological aspects of sustainability [22]. In general, the social side of engineering tends to be downplayed [56]. Indeed, we saw marked increases in the cultural and economic considerations students made in their reports.

While there was still room for improvement in all societal considerations for innovation, sustainability represented the most thorough consideration for the majority of the 19 student teams by the end of the course. Ethical considerations and collaboration were less consistent, even though improvement was seen in all categories except for privacy considerations. In the current data set, privacy, fairness and co-creation in particular remained overlooked or only superficially mentioned by most of the student groups, even though fairness and co-creation considerations did increase from the initial reports. In fact, co-creation, diversity and responsibility considerations have shown the most significant increase by the end of the course. Yet, the average semantic distance rankings remained relatively low in these categories. Innovation and design decisions involve making decisions on whose needs and desires to privilege - and at whose expense [57–60]. While tradeoffs may be inevitable, we need to strive towards making informed decisions - yet the lack of discussion around these core topics in the current report data suggest that many engineering students do not consider, let alone have the skills to successfully address these core issues.

As the current study is limited to a single course and fairly short (two to four page) written assignments, more research is still clearly needed to develop a wider and deeper understanding of how engineering students incorporate societal concerns in their problem solving efforts. Therefore the results are not generalizable as such. However, from a practical perspective, the results are encouraging in the sense that a relatively minor intervention enabled engineering students to apply a broader range of societal considerations in scoping innovation projects. Thus, we encourage other institutions to introduce societal perspectives of innovation into teaching. Nevertheless, we acknowledge that succeeding in this kind of an introduction to societal issues in engineering education may require an existing culture of interdisciplinary, cross-cutting teaching and learning that provides a fertile ground for change. Longitudinal studies extending beyond the time frame of single courses are needed to evaluate whether these changes stick and transfer to other innovation and problem solving efforts.

On the other hand, the coding scheme developed in this study can be used for other deliverables to identify which areas might benefit most from added instruction or to evaluate the effectiveness of interventions. In the studied course, for example, ethical considerations were identified as lagging behind other considerations even after the intervention. Given that co-creation also remained fairly low, future studies could investigate whether project-based courses with interaction with external stakeholders are effective in increasing such considerations. Additionally, future research could also explore how different forms of interdisciplinary collaboration affect societal considerations - solving sustainability problems requires integrating knowledge from various scientific and societal bodies of knowledge [61]. While some knowledge in all societal aspects can be considered beneficial for responsible innovation, engineering students can also be well-served by being able to identify which professionals and disciplines they need to involve in their efforts to overcome limitations in their own capabilities. Broadening the societal considerations of engineering students may require broadening both their access to experiences with dealing with societal considerations in problem solving within engineering education, as well as access to opportunities to bridging their expertise to the array of other disciplines required to address these issues in concerted efforts.

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Appendix. Coded rankings of the considered nine societal themes in the first and final reports of 19 student groups.

	VISION STATEMENTS									FINAL PROPOSALS								
GROUPS	Environment	Culture	Economy	Privacy	Fairness	Responsibility	Diversity	Co-creation	Stakeholders	Environment	Culture	Economy	Privacy	Fairness	Responsibility	Diversity	Co-creation	Stakeholders
A	4	0	2	0	0	0	0	0	0	1	1	3	0	1	2	3	4	2
B	5	0	3	0	0	4	0	0	0	4	0	2	0	3	4	4	4	5
C	4	0	1	0	0	1	0	0	0	3	2	5	0	1	2	1	0	1
D	4	4	2	0	1	3	1	1	2	5	5	0	0	3	5	2	2	1
E	2	2	2	5	1	1	1	0	3	2	3	4	5	3	3	3	2	5
F	3	1	1	0	0	1	1	1	1	4	3	3	0	1	3	3	4	1
G	4	1	3	0	1	2	2	0	2	5	2	4	0	1	3	4	2	3
H	3	2	1	0	2	2	1	0	2	4	4	4	0	1	4	3	2	4
I	3	0	1	0	0	1	1	0	0	5	4	2	0	0	3	2	1	2
J	4	1	3	0	1	2	1	0	1	4	1	4	0	2	3	3	2	3
K	3	2	2	0	0	1	1	0	1	4	3	2	0	2	3	2	4	4
L	4	2	2	1	0	1	1	0	1	4	3	3	4	2	5	2	2	4
N	3	1	2	0	1	1	2	0	1	3	3	3	1	2	4	3	3	3
O	3	2	3	1	1	1	2	0	2	4	3	4	0	3	3	2	0	2
P	4	2	3	0	1	2	3	0	3	3	3	3	0	2	4	3	3	3
Q	2	4	3	0	1	1	2	0	2	1	5	3	0	4	4	3	1	3
R	3	0	4	0	1	1	2	0	2	3	1	3	1	2	3	3	3	3
S	3	1	2	0	0	1	0	0	0	4	3	4	0	1	4	4	3	5
V	2	2	3	3	3	1	1	0	2	3	2	4	4	4	4	2	2	3
Average	3,32	1,42	2,26	0,53	0,74	1,42	1,16	0,11	1,32	3,47	2,68	3,16	0,79	2	3,47	2,74	2,32	3
Median	3	1	2	0	1	1	1	0	1	3	3	3	0	2	3	3	2	3