Environmental considerations in engineering systemic differences between experts and novices

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ENVIRONMENTAL CONSIDERATIONS IN ENGINEERING: SYSTEMIC DIFFERENCES BETWEEN EXPERTS AND NOVICES

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ABSTRACT

Engineering knowledge forms an essential part of our planetary fight against climate change. Traditionally, engineering curricula emphasizes the importance of technical knowledge and encourages to specialize in niche areas, where engineers develop themselves into experts. However, it is important to be able to reflect on complex societal challenges from a variety of perspectives to produce not only innovative, but also long-lasting and inclusive solutions for the greater good. This paper aims to understand the extent of systems thinking abilities of engineers by differentiating experts from novices. The study traces sustainability connections made by professional engineers and master's level engineering students when solving engineering design problems. This qualitative study highlights seven recurring themes that relate to the global sustainability discourse and describe a problem-centred approach through a real-life case that focuses on paper and pulp production, through a thematic analysis of 59 responses. The results portray system-level differences in how novice and expert engineers approach sustainability questions and how these differences shape their solution spaces.

Keywords: Sustainability, Societal consequences, Social responsibility, Systems thinking, Experts and novices

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1 INTRODUCTION

A grand challenge the humankind is facing, fighting global warming, and reducing if not reversing the effects it has on our planet and life on it, demands action from engineering professionals as well. Engineers are expected to contribute to these grand challenges through radical innovations that heavily rely on technical knowledge. However, the ever-growing complexity of our planetary challenges requires engineers to not only be aware of societal consequences of the innovations they are working on, but also asks them to develop a systemic understanding. Therefore, in this study we have adopted the holistic three-pillar conception of sustainability (e.g., Purvis et al., 2019), and tried to understand sustainability through three inclusive angles: social, environmental, and economic sustainability.

Companies are creating and implementing sustainability programs (e.g. White, 2009; Baumgartner and Ebner, 2010; Dasom and Hess, 2022) and drafting corporate responsibility reports. Universities are incorporating sustainability into their teaching and curricula that are designed to educate future engineers to be able to understand and tackle sustainability challenges (Hayles and Holdsworth, 2008; O'Byrne et al, 2015). According to the previous studies, engineers can make good environmental connections already before having broadened their perspectives through sustainability education (Celik et al., 2020), but less is known about the connections that engineers make when they are asked to create an understanding of the environmental connections of a case at hand. Moreover, psychological distance from climate change is a phenomenon that affects our ability to understand especially the distant impacts of climate change, but it might also have an opposite effect on promoting sustainable behaviour (Spence et al., 2012). Also, developing empathy towards sustainability can either create positive actions, attitudes, and intentions or result in false self-evaluations of one's solutions (Alzayed et al., 2022).

The development of knowledge, that is linked to empathy, thus deep understanding (Kouprie and Visser, 2009) of sustainability can be developed through education, and is something that is distinctive to experts. It is known that experts are aware of the need for and the resources of information when facing engineering problems (Björklund, 2013). Björklund (2013) relates the ability to make in-depth, detailed and connected mental representations of engineering problems to expertise, which enables individuals to form comprehensive solution directions. Expertise is a widely discussed topic in the literature as the notion of expertise is difficult to capture. This is because regardless of the field, expertise is defined through a series of complex and interdependent parameters ranging from tenure to exceptional output (Walton, 1997, Burgman et al, 2011), but also because expertise is subjective and uncertain in its nature as the acknowledgement comes typically from other experts in a specific field). In this study, we adopt Horn and Masunaga's (2006) definition of expertise when talking about the differences between novice and expert engineers that underlines knowledge, ability to reason, and memory as the three main attributes of expertise. Authors highlight the deductive reasoning skills that derive from initial knowledge of experts and their ability to make flexible use of information when necessary (Horn and Masunaga, 2006).

Sustainable engineering design requires experts' abilities to make connections and create understanding. However, in most engineering design cases, sustainability and sustainable engineering are not in the centre of the engineers' expertise by education or experience. When solving complex societal challenges, holistic and systemic understanding of the related connections of the systems that the solution is expected to influence is needed (Celik et al. 2020).

The current study aims to answer the following question: What are the differences in making system-level sustainability connections between professional engineers (experts) and engineering students (novices) when understanding engineering design problems? Many scholars looked at the role of expertise in product development and problem-solving capabilities in the fields of design and engineering by comparing novice and experts, but the research on their understanding of complex societal challenges, which is an essential step towards defining the solution space prior to operationalising technical knowledge is scarce. Additionally, research shows that engineers can create empathy or psychological distance to sustainability, but the link between the expert and novice abilities to recognize sustainability connections remains unknown.

2 METHODOLOGY

2.1 Data collection and case context

This study on novice and expert engineer's capabilities of identifying environmental concerns and bi-directional connections embedded in a complex engineering case with societal indications builds on data collected in three complementary parts.

First, two company representatives from the case company were interviewed on a product development project with an outcome already in the market, to draft the case. After having gained an understanding on the case, the interviewees were asked to name sustainability/society connections they could identify either having an effect on or being affected by the project and product. Second, in-depth interviews were conducted with two mechanical engineering faculty members (a professor and a lecturer) asking them to analyse the case from given perspectives identifying sustainability linkages. Third, 55 individual student responses from advanced mechanical engineering students were collected to represent the novice perspectives. These responses were collected within a master's level course focusing on the impact mechanical engineering has at large. The course provided a fertile ground for running a pilot on teaching holistic problem solving through a design thinking approach emphasising the abilities to incorporate societal issues to given technological challenges.

As a course assignment the students were instructed to choose one of three given company cases (all formed in a similar manner through company interviews with two representatives per company. The students were offered optional cases to cater for different interests of the students.) and deliver short, individual analysis reports of roughly 1,5 pages, in which they were asked to discuss the chosen case through PESTEL analysis (stands for Political, Economical, Social, Technological, Environmental, Legal) (Aguilar, 1967; Gillespie, 2007), writing approximately 200 words on each letter enabling them to articulate their insights on these various aspects. The same PESTEL-framework was used in the company and faculty interviews. The students were asked to mention at least two connections per letter and do adequate research in addition to familiarising with their chosen case. Also, depth and reasoning were asked for. Their answers were graded letter by letter, on a scale from 0 to 3 points. The grades were not considered in the analysis presented here.

This paper focuses on one of the three cases, one that 55 of the students chose to work with. This is to make sure the students' answers are comparable against each other. The chosen case focused on a company developing and supplying technologies, machinery, and systems for e.g., paper industries, and their efforts in developing a new calender. Environmental connections ("E" in PESTEL analysis) made by the students, faculty, and company representatives were taken as the focus. The company representatives and university faculty members are considered experts in the topic of solving complex mechanical engineering problems, as they either have been solving the problem at hand or teach to solve similar problems, which is in line with definitions of expertise (Bourne et al. 2014). However, we do acknowledge that their expertise and perspective are different from each other's.

2.2 Data analysis

The responses of novice and expert engineers were analysed through a systemic sustainability lens that aims to look beyond environmental concerns when discussing sustainability (Sterling, 2004; Scoones et al., 2020) This analysis enabled us to explore the common topics in the responses of both novice and expert engineers. Between the found commonalities among responses, a thematic analysis was performed to identify emerging patterns, which were later used to shed light on the differences between novice and expert groups. Thematic analysis refers to the process of breaking down the bits of information into themes in a qualitative data set (Braun and Clarke, 2006).

The perceived environmental connections from students' and experts' PESTEL analysis responses were thematically coded. First, recurring mentions of connections were categorised, resulting in seventeen initial categories in the expert and eighteen in the student responses. Similar categories were further clustered into seven themes based on their thematic similarity (Braun and Clarke, 2006). The categories are further discussed in the results chapter.

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The themes and their respective subcategories were divided into three levels, presented earlier by Luo et al. (2021) based on the level of depth of the responses in the representation of their environmental considerations: system level, subsystem and interactions level, and detail level.

3 RESULTS

Comparing the novice (N) and expert (E) considerations revealed differences in system-level considerations regarding sustainability concepts in novice and expert engineers. Seven recurring themes mentioned by both experts and novices were found. However, there were differences in on what level the novices and experts were able to consider the connections. The results suggest that expert engineers were more likely to make connections on sub-system and interactions or details levels while novices were more prone to consider system-level connections (Table 1).

Table 1. The themes and subcategories by contributor (novice and expert) and level

Theme	Infor-mant type	System level subcategories	Subsystem and Interactions level subcategories	Detail level subcategories
Environ-ment and biodiversity	Novice	-Environmental friendliness -Environmental regulations	-Climate change solutions and responsible practices -Deforestation and biodiversity	
	Expert	-Reducing the effect on biodiversity		-Raw material sourcing (less trees)
End product	Novice	-Paper recycling	-Paper consumption	
	Expert			- Final product replacing plastics as packaging -No surface treatment for better recyclability
Carbon emissions and footprint	Novice	-Decreasing carbon footprint	- Deforestation to help carbon emissions -Planting trees for paper production	-Pollution from factories and used paper
	Expert	-Overall impact on carbon footprint -Helping global warming		
Raw materials	Novice	-Resource efficiency (less material used for paper)	-Raw material transportation	-Higher product quality (less waste)
	Expert	-Resource efficiency (less material used for paper)	-Raw material transportation	-Less impact on the whole ecosystem when less material used -Better operational reliability (less loss)

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Environ-ment and economy	Novice		-Climate change and environmental issues as a selling point	
	Expert		-Sustainable products as a selling argument	
Production process	Novice	-Cutting material usage (in machine production) -Energy consumption in producing machine		-Recycled materials for making the machine
	Expert			-Less resources tied to the machine
Energy	Novice	-Energy consumption in paper processing		
	Expert	-Less energy needed and/or used	-Less energy gone to waste	-Process produces energy - Surface treatment alternatives, less chemicals - Health effects

3.1 Environment and biodiversity

On the system level, the connections in this theme were made to general environmental friendliness (N), environmental regulations that might have guided the development of the new device (N), and general reduced effect on biodiversity (E). The novices saw the regulatory pressure as one clear connection but discussed it on quite a general level. The only expert connection on this level was the reduced effect on biodiversity due to the new technology. One novice drew a connection to environmental friendliness as follows:

“In order to reduce environmental harm, [case company] should research on how to make paper production environmentally friendly and try to be proactive in order to achieve these goals.“ (novice)

On the subsystems and practices level the novices’ focus was on climate change solutions and responsible practices and the effect logging has on deforestation and therefore nature as a whole. The experts did not make connections on this level regarding environment and biodiversity.

“[The case company] should adopt responsible production practices and encourage responsible “The Company X plans to modify how the company operates to minimize greenhouse gas emissions. Upon research, it is discovered the operations are responsible for about 1% of the carbon footprint. (novice)

Only experts drew detailed level connections, and they noticed how the new technology reduces the need for sourcing raw material, which in return leads to less logging and through that has a positive impact and/or a link to biodiversity.

“But in the best case as much as 10 percent of raw material has been saved, which here means that the savings come from everything. Starting from the forests, so out of these trees you can leave ten (%) in the forest to grow.” (expert)

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3.2 End product

When focusing on end-products, which in this case is paper, novices and experts make connections of different depth. Novices primarily discuss system and subsystem levels and focus on the recyclability of the end product in very general terms by identifying the systemic impact recyclability can make.

"The conversion of biomass into renewable energy and recyclable materials, including pulp, paper, board, and tissue, is a speciality of Company Xt. … Since Company X's solutions are aimed at industrial processes like pulp, paper, and energy production, increasing process efficiency, using air pollution control technology, and swapping out fossil fuels and materials for renewable ones can all significantly help the environment." (novice)

Additionally, novices relate sustainability also to the consumption of the end product on a subsystem level, suggesting that with the new technology Company X is able to make high quality paper, which in the long run decreases paper consumption.

"The improved machine creates a more efficient paper production method. It can use less resources for the same amount of higher quality product. These sorts of innovations that create more sustainable products are important in terms of trying to solve problems regarding climate change." (novice)

Experts on the other hand, make much more detailed, material-level connections to sustainability when talking about end-products. For instance, interviewees talk about different applications of the end-product that play a role in its recyclability such as the finish of the paper as the next quote illustrates (glossy, matte, vb.). Also, experts relate the issue of recyclability and its impact to various areas of application to create greater environmental value.

"Well it is a clear environmental effect, that when paper is treated for surface, and surface treating paper is foolish - - and calendering offers an alternative to surface treatment. Of course it is not the same, but if treatments are not needed, the recyclability and reuse of the paper is notably easier." (expert)

3.3 Carbon emissions and footprint

Carbon emission was strongly linked to use of natural resources during the production of paper both by experts and novices. In this theme category, experts only referred to systems level and refrained from engaging into higher levels of detail. However, since paper production heavily relies on forestry, this natural link was underlined several times. On systems level both novices and experts referred to the need and possibilities of decreasing carbon footprint of paper production industry:

"[if material savings are big enough] the carbon footprint is reduced equal to the amount that operating the whole [paper] plant produces in CO2. So this is a huge deal through CO2." (expert)

On subsystem level, novices related the innovations in the production process to decreasing deforestation and therefore increasing/protection of biodiversity in forests. Additionally, novices referred to contemporary practices such as planting trees for paper production and therefore made cross-industrial links between engineering and agriculture:

"The need for wood overall broadens the forestry in Country X, leading to more forest plantations. Since one tree will take up about 22kg of CO2 from the atmosphere, will the rise of forests majorly increase the natural CO2 absorption in Country X. As long as the wooden products are not burned, the CO2 remains trapped in them." (novice)

On detailed level novices referred to the future plans of the company regarding decreasing carbon emissions for the greater good and discussed how resorting to renewable resources can make an impact on this topic by giving very specific and operational examples:

" The company plans to cut CO2 emissions from its own operations by 80% within the 2030s. There are multiple methods that the employees are taking, such as switching to renewable energy sources

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from fossil fuels in the company locations, buying district heating and carbon-free electricity, and improving energy efficiency.” (novice)

3.4 Raw materials

Many connections made were linked to raw material usage of the end product paper. On systems level both novices and experts considered the effect the case had on needed raw material, noticing that with the same amount of raw material more paper could be produced, leading this to be an important environmental connection, as the next quote illustrates.

“With digitization, the consumption of paper has decreased, but it is still at a high level. About 60 kg per person per year. It is interesting to see what kind of value promises can be made thanks to continuous development. Thanks to this innovative invention, it is possible to use considerably less raw material, which is clearly positive news for our nature.” (novice)

On the subsystems and interactions level both groups made again the same connection, which was the effect decreased need for raw material had on transportation and the environmental effect that logistics have as one expert quotes:

“For example, an ice cream carton is a good [example], if you can make it with less raw materials then transportation, trees themselves, everything saves the environment and energy and so on.” (expert

3.5 Environment and economy

Within the environment and economy category, both novices and experts reflected on the business advantages of having sustainable practices and made a connection to economic systems and both novices and experts remained on subsystem level. Novices argued that companies who portray environmental sensitivities and act on them have a more positive public image, and therefore are more likely to survive in the global market. One novice quote:

“Environmental and sustainability aspects and concern for climate change and the environment are massive factors among businesses. They play a huge part in displaying company’s image to the public and stakeholders.” (novice)

Experts discussed the economic value of environmentally friendly products from the perspective of getting justification to the development of the case product and getting the product to the market. One expert drew the following connection:

“[sustainability was not really a driver for development but rather that aspect has surfaced later, as money is behind everything.] The customers make money and if they can make money and if they can make good profit with sustainable and environmentally friendly products then it is fine.” (expert) (1)

3.6 Production process

Cutting material usage and using recycled materials were the focus points for both experts and novices when talking about the process of production. On system level, novices not only highlighted the importance of decreasing use of materials in the production of the machinery itself as a means of decreasing energy consumption in the process, but also referred to company’s use of other forms of resources management such as innovating for decreasing air pollution or their innovation son organisational innovation:

“The environment can be greatly benefited by improving process efficiency, employing advanced technology to manage air pollution, switching from fossil fuels to renewable ones, and implementing Company X’s solutions in industrial processes like pulp, paper, and energy production. Company X also developed remote working for employees to significantly reduce business traveling emissions.” (novice)

In this category, novices also made technically detailed links by stating the importance of using recycled parts when producing the machinery and the environmental effects of this decision. Despite

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the level of detail on technical systems, novices were also able to make cross-industrial links that identify benefits of using recycled parts. One novice quote:

"[The case company's] decision to buy old machines for the prototype from [another country], helped the environment. By using second hand machines, there was no need to buy new parts. This meant that no new metals were mined, and no machinery was needed to produce these new parts. According to "Our world in data" website around iron and steel industry produces 7.2% and machinery produces 0.7% of the world's total emissions. Energy and emissions were saved because of this decision." (novice)

Experts on this category remained on detail level by referring to the opportunity to tie less resources to the production with the new technology that the case company developed as stated by one expert:

"If we compare [to another type of calender], this is much simpler, and does the same thing with less resources. - - All the needed materials, raw materials, and use is so, that if you compare - -"(expert)

3.7 Energy

In the category of energy, both novices and experts primarily focused on the need/used energy during the production. Novices that reflected on this aspect could only reflect on energy consumption during the production process in general terms without engaging into technical details of the process and therefore remained on the system level. One novice quote:

"Company X's metal belt calendaring enables improvements in environmental aspects of paper production. The product has been able to increase yield and decrease raw material consumption, which enables less resource-intensive manufacturing. Furthermore, higher yield will also result in less energy consumed per unit manufactured." (novice)

Experts on the other hand were able to approach the topic of energy from a multitude of perspectives that include need, waste, alternative treatments. On system level experts followed the novices's line of thinking and commented on energy needed for the production line. On subsystems levels the experts related the topic of energy to waste, as in, with new innovations Company X is putting forward, the production line will also be wasting less energy and therefore carbon emissions will be reduced. On detail level, experts referred to a variety of technical matters such as the use of chemicals in paper production that lead towards undesired health effects. On this level, one expert referred to the energy production opportunities that are to be found in the process and stated:

"Some energy is also produced in these processes - was it black lye - well anyway, if energy consumption can be cut, then this does not…" (expert)

4 DISCUSSION AND CONCLUSIONS

Results of this study point out that regardless of their area of operations, experts are able to tap into their knowledge in specific fields and make more in-depth connections, where practical and technological aspects of sustainability are underlined. This is in line with the definition of "expertise" in the literature as it is consensually defined through a certain depth of knowledge, reasoning with deductive processes and the ability to understand the details of a problem that are most important (Horn and Masunaga, 2006, Bolton et al. 2021). Novice engineers on the other hand, can make wide and globally applicable linkages of environmental concerns. They were able to explore the problem space further than the given boundaries and make links to greater societal and environmental issues that do not only concern the local context but operate on a global scale. The experts did not mention these system level connections per se, but their answers indicate they identify the connections but are prone to dive deeper into detailed considerations. We argue that this difference stems from the difference between expert and novice approaches towards problem solving. Multiple studies ranging from the field of education to medicine highlight the deductive nature of expert knowledge that tends to first categorise and organise information at hand (Groen and Patel, 1985, Swansson et al., 1990). This pattern does not only contrast with the explorative nature of the novice approach, but also with the inherently systemic nature of sustainability issues that our study deals with. Yet, the discussion on the difference between expert and novice approaches remains inconclusive in the literature and evidence from the design discipline is scarce.

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The relationship between the complexity of the challenges earth faces and the engineering knowledge is a paradoxical one. On one hand, the complexity of societal challenges that our planet is going to be facing in the very near future, requires engineers to be able to develop system-level interventions that can only be achieved with obtaining a holistic overview. Being born into an abundance of multimodal communication channels, engineers that are currently novices are naturally able to inform themselves through a variety of resources and perspectives (Turner, 2015). This enables them to look beyond the problem at hand and make connections that operate in an interdependent series of systems and subsystems. The curricula they study, that growingly underlines systems thinking skills also helps them to pursue this approach (Chiu, et al., 2019, York et al., 2019). However, on the other hand, engineers are also expected to scope and operationalize the technical solutions they develop and achieve technological advancement. The practical side of the profession requires engineers to specialise in different layers of application, which then demands an in-depth understanding of technological developments.

Expert engineers on the other hand can channel their understanding towards technological aspects of the issue at hand and operate on a highly practical scale. We argue that both are needed; the ability to identify and expand the system level connections as well as the ability to dive deeper in the case at hand and see the subsystem and interaction, as well as detail level connections and implications a problem and possible solution to it might have. While we can see that it is beneficial to understand the system level while being able to pinpoint details, how can we balance this? The challenge engineering schools are facing in their curricula relates to this paradox as well. How do we encourage specialisations that enable novices to produce applicable solutions to engineering problems without sacrificing their inherent ability to see the world as an interconnected series of systems?

We suggest that the ability to recognize environmental concerns might give indications of the engineers' ability to integrate these into practice when solving engineering problems. However, the results are encouraging regarding the understanding of differences in approaches of novice and expert engineers to sustainability problems. Results especially point out the value of the systems thinking efforts we make in our curricula to open the solution spaces of engineering students. We highly encourage the inclusion of systemic perspectives and societal considerations into engineering problems before allowing engineering students to dive into their specialisations in the field to become fully equipped experts.

The current study has limitations. First and foremost, there is a quantitative difference between the number of novice responses and expert responses. This limits us from performing a reliable statistical analysis to compare the occurrences of the connections that were made. Also, as the study is limited to short writing assignments on the novices' side, from the context of a single master's level course for mechanical engineering students, more research is needed for developing a wider understanding of both novice and expert perspectives. On the expert's side, only company representatives who are highly engaged in the process and teaching staff were interviewed. A more inclusive data set would possibly deliver clearer results on expert perspectives.

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