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The Socio-Technical Connection is Plastic, but Only When Design Starts from Need Formulation

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Introduction: New engineering challenges and engineering education

Engineering education has over the years shifted its focus from being a practical and hands-on workshop to theory-based design, where the emphasis is on formal declarative knowledge, captured through engineering sciences and mathematics, and transacted primarily through classroom situations. Engineering practice in turn got narrowly defined as technical problem solving, based on formal knowledge. But to compete in the workplace of the 21st century, and to meet the challenges of globalization, sustainability, and social equity, students require a close understanding of the social and environmental contexts along with the technical -- particularly broader cultural knowledge, team skills, and values beyond techno-centricity.[1,2,3,4]

To reform engineering education in a way that it can address these current and emerging engineering challenges, many countries have modified their accreditation requirements to include the knowledge, skills, and values necessary to address these issues. In the USA, the focus shifted from 'credits completed' to 'outcomes achieved'.[5] Institution of Engineers, Australia, updated the procedure for accreditation of the engineering baccalaureate to ensure inclusion of sustainability learning.[6] Curricula were modified to include courses in Sustainability, Humanities and Social Sciences, Ethics, as well as soft skills such as writing, communication and team work.[7,8,9] Strategies for pedagogical reforms included cornerstone and capstone courses, project and problem-based learning, active participatory learning opportunities, instructional laboratories, learning a second language, and foreign country internships.[10,11,12,13]

Nevertheless, most engineering education programs continue to emphasize the technical aspects, while the social and environmental aspects remain externalized.[14] Barbara Olds[15] notes that “the education of science and engineering students has for too long been merely “technical”, often neglecting human complexity in order to achieve quantifiable correctness. Colleges and universities focus too narrowly on specialization, and produce graduates who are neither professional nor personal successes. More and more educators argue that science and technology students must be more liberally educated; recent reports on education are cases in point.”.

To the extent that sustainability concepts and active-learning methods were integrated into the curricula, it was found that there are barriers hindering the re-orientation of engineering curricula toward “sustainable” engineering.[7] The main broadening experiences, coming from elective courses in the humanities and social sciences, remain peripheral.[16] Based on a study of practitioners' responses to a sustainable-design challenge, Mann, Radcliffe, and Dall’Alba[17] stress the need for a pedagogical model that helps develop students as professionals, which is different from a standard instructor-led learning model. As a counterpoint to such broadening efforts, Anderson, Courter, McGlamery, Nathans-Kelly, and Nicometo[18] find that “engineers are seen to be frustrated by non-engineering work.”.

These, and other studies reviewed in the next section, point to a two-fold gap. One, students lack knowledge of the social and problem contexts/requirements, and are not trained in ways to address them. Particularly lacking are need/problem identification and need/problem framing skills, which are required to address complex and messy real world problems. Second, students develop values that are too technology-centered, and this leads to them moving away from the social and environmental components of the engineering problem space. These gaps limit students' abilities to innovate and develop socially-engaged engineering solutions.

In this paper, we examine current engineering education research into these two issues, and explore how further insight into these issues could be provided by the study of a specific socially engaged engineering practice, which we term grassroots design and engineering. In this practice, engineering problems that are not addressed, or are often ignored, by formal engineering practitioners, are solved by rural people not educated in engineering, and sometimes by formally trained engineers who specifically focus on such problems. In the case study we report, we compare the design process as seen in the grassroots problem-solving practice of a formally trained engineering professional (EP), with a canonical formal engineering design process, to understand what EP needed to learn beyond the canonical model to practice grassroots design and engineering. We particularly focus on where and how social and environmental concerns/factors interact with EP's technical knowledge, and whether/how this influences the resulting society-technology connection. We explore how such case studies of grassroots practice can inform student understanding of engineering as a socio-technical enterprise.

The paper is structured as follows. In Section 1, we provide an outline of research in engineering education and practice that highlights and seeks to address the two-fold gap identified above. Section 2 focuses on engineering design, which is the specific aspect of engineering examined in this paper. Section 3 outlines a case study and analysis of the design practice of an engineering professional, as EP addresses a grassroots engineering problem. Section 4 discusses the implications of this analysis. We close with a conclusion section.

Section 1: The need for a socio-technical understanding of engineering

A core component of Engineering Education Research (EER) focuses on the differences between classroom problems and workplace problems, and points to the need to prepare students for real-world problem-solving. “If students are to learn to think like engineers, they must be challenged to solve authentic, complex problems.”[19] Donald Schon[20] observes that “In the terrain of professional practice, applied science and research-based technique occupy a critically important though limited territory, bounded on several sides by artistry. There are an art of problem framing, an art of implementation, and an art of improvisation – all necessary to mediate the use in practice of applied science and technique.”.

Contrary to this real-world practice, engineering curriculum and pedagogy implicitly encourages a dichotomy between technical and social context, and a 'technical rationality' based problem-solving image of engineering. This results in a student identity that is exclusively technical in its character. Louis Bucciarelli[21] highlights this issue: “The way we structure our curriculum and teach our subjects all conspire to instill in the student the idea that engineering work is value-free. Object-world work may be, but that is but one part of engineering competence. While teaching the “fundamentals” of science and mathematics, and the engineering sciences, remains necessary, we must do so in more authentic contexts, showing the uncertainty and ambiguity inherent in problem setting as well as solution, and how social and political interests contribute in important ways to the forms of technologies we produce. We ought not as faculty claim, or imply, that solving single answer problems or finding optimum designs, alone, uncontaminated by the legitimate interests of others is what engineers do all of the time. This is irresponsible.”. He adds that “In engineering we take pride in teaching “the fundamentals”. It’s time to explicitly recognize that what is fundamental to engineering practice goes beyond the scientific, instrumental rationality; to fail to acknowledge this is “just about unethical”.”.[21]

Wendy Faulkner[22] observes that “Their educational grounding in mathematics and science allows engineers to claim an identity in the material and (mostly) predictable phenomena governed by the 'laws of nature', backed up by a faith in cause-and-effect reasoning. And this same materiality and scientificity enables them to claim, as the central contribution of engineering design, that it creates technologies that 'do the job'. This is a very empowering identity...”. Using the example of one of the engineers she shadowed in her study, Faulkner explains that “Karen juxtaposes the 'upfront' roles with the more 'backroom' job of detailed design, in a way that echoes the technical/social dualism. She has a sense that the upfront roles are less 'real' engineering, perhaps because they are further away from the materiality of 'producing' things.”.[22] Quoting another engineer say, “The world would be great if it weren't for people!”,[22] Faulkner explains that “I read this comment as an ironic dig at the technicist version of engineering, and a recognition that the 'people aspects' of engineering are far more challenging and difficult to resolve than the 'nuts and bolts'.”.[22]

Studies of the practice of engineering document that engineering is not merely or mainly a technical, or techno-scientific activity, but is rather a socio-technical enterprise, and indicate that educational reforms are necessary not only for learning engineering knowledge and skills, but also to develop socially engaged attitudes and values. We review these studies by highlighting three key social aspects of engineering: a) engineering (problems and) products are socially constructed, b) engineering process is socially distributed and culturally situated, and c) engineering activity (and output) has social responsibility.

a) Engineering products are socially constructed

Science and Technology Studies (STS) of professional engineering work suggest that “Technological systems contain messy, complex, problem-solving components. They are both socially constructed and society shaping.”.[23] Analyzing the case of the introduction of an electric car (VEL) in France, Thomas Hughes[23] points out that “... it is often believed that at the beginning of the process of innovation the problems to be solved are basically technical and that economic, social, political, or indeed cultural considerations come into play only at a later stage. However, more and more studies are showing that this distinction is never as clear-cut.”. Engineers are system builders, and technological problem-solving involves integrating heterogeneous elements such as humans, the environment, and technology, a practice termed by John Law as 'heterogeneous engineering'.[24] Stevens, Johri, and O'Connor note that “... the social and technical are almost inextricably tied up together in any engineering project ..."[25]. Lucy Suchman, through the analysis of a bridge building project, demonstrates that apart from the design and technical work, the organizational activities of sense-making, persuasion and accountability, considered by engineers to be somewhat peripheral, are essential, to the 'real' work of design.[26] Vermaas, Kroes, van de Poel, Franssen, and Houkes[27] argue that engineering is "the result of social negotiation processes in which the various groups involved, including customers but also producers, articulate their wishes and needs. The function of the product that is to be developed is thus a social construction that is based upon what divergent groups consider to be 'desirable'.".

b) Engineering process is socially distributed and culturally situated

Engineering involves teamwork and communication with other engineers as well as non-engineer stakeholders.[28,29,30] "The foundation of engineering practice is distributed expertise, enacted through social interactions between people: engineering relies on harnessing the knowledge, expertise and skills carried by many people, much of it implicit and unwritten knowledge. Therefore social interactions lie at the core of engineering practice."[31]

This point is well illustrated by Matthias Heymann[32], using an analysis of the development of Danish wind technology. The Danish wind turbine designs turned out superior to the US and German ones, which focused exclusively on technical specifications and big scales, leading to operational failures. Heymann argues that this superiority emerged not only because of differences in knowledge bases and engineering mindsets, but also because of social interaction of different groups (particularly engineers and windmill artisans), facilitated through journals, social forums, advocacy, and test stations, as well as the role played by the techno-political settings. Heymann points out that culture and context act not as external constraints, but are a part of the design process, towards which engineers cannot afford to be reductionist, ignorant, or insensitive. "Engineering curricula with a strong focus on science and technology rather conceal these economic, political and cultural settings, of which engineers are an influential part. If students learn to develop awareness for this condition, if they learn to perceive themselves as a part of a larger culture with influential and conflicting values and goals, then they may more easily develop the political and cultural sensitivity required in technological development and innovation."[32]

c) Engineering activity (and output) has social responsibility

In discussing the social role and responsibility of engineering, George Bugliarello[33] comments that "engineering has performed extraordinarily well in responding to technical challenges but has shied away from the vigorous pursuit of complex sociotechnological issues." He adds, "Any attempt to rate the current performance of engineering in the satisfaction of social needs must take into account at least three factors: (1) the fundamental difficulty that engineers encounter in addressing major social problems given a lack of an adequate sociotechnological preparation, (2) the propensity of engineers to find technological fixes for existing social systems rather than to develop and use technological innovations to accomplish needed social change, and (3) the ensuing limited or simplistic views of the social role of engineering.".[33]

In the analysis of Danish wind technology development, Matthias Heymann[32] emphasizes that "... engineers are not acting free of political and social values, but are part of social groups and carriers of convictions and ideologies. Second, technologies carry non-technical values, commitments and goals (which may be perceived differently by different actors and social groups).".

The state of engineering education

Contrary to what these studies show, engineering education has focused exclusively on the technical aspects, and this has created a professional profile that is detached from society, unlike other socio-technical professions such as medicine, law, and management. "The failure of the engineering curricula to address attitudes and values systematically has had unfortunate consequences. Engineers often make decisions without feeling a need to take into account any of the social, ethical, and moral consequences of those decisions, believing that those considerations are in someone else's purview."[34,35] Stephen Petrina[36] suggests this is due to the lack of an integrated understanding of how closely building is related to its socio-political and ecological consequences. "When we design, and teach design and technological problem solving, however, we invariably neglect the interconnectedness of products, streams, and wakes."[36]

Vanderburg and Khan[37] observe that in the formal undergraduate engineering curriculum, "Technological development is primarily guided by values and measures such as efficiency, productivity, cost-effectiveness and profitability. These measure how much output can be derived from certain inputs, but they tell us nothing about how any technological development will fit into and be compatible with human life, society and nature.". Herkert and Viscomi[38] suggest that "... engineering departments need to design specific courses for engineering students rather than just including a few humanities courses in their curriculum.". However, many researchers across domains, including Dunfee and Robertson[39], suggest that ideally ethics must be integrated throughout the curriculum into as many courses as possible. Caroline Bailie, Donna Riley, Juan Lucena, George Catalano, and other scholars in the area of engineering and social justice extend the argument for ethics education to the consideration of social justice questions, through critical pedagogy.[40,41,42]

Based on several studies to understand the relationship between engineering profession and social responsibility (as reported by students based on their educational experience), Canney, Bielefeldt and their colleagues[43] found that "... the ways in which students talk about the interaction between engineering and society remained mostly at low level, bare minimum relationships of public safety and providing infrastructure. Few students talked about collaborative or co-creative relationships between engineering and society.". They suggest that "In order to develop engineers with a broader understanding of the societal and cultural contexts in which they work, the students must first be guided to have broader views about how engineers and communities are to interact.".[43] In another study to explore which courses, topics, and pedagogical methods the engineering students found influential to their perspectives on social responsibility, they report that for 42% students, "none of their college courses had influenced their views.".[44] "Topically, students seem to be positively influenced by discussions of ethics, as well as sustainability and environmental issues. Students seem responsive to project-based and service learning pedagogies as tools to help their social responsibility development."[44] Based on these studies, they present a framework (PSRDM) to understand the development of social responsibility in engineers, rooted in the Ethic of Care.[45]

A more radical view argues that "Engineering education is a major channel to corporate power" and engineers is a 'domesticated breed' that "in reality served only the dominant class in society".[46] Erin Cech[47] reports that "... engagement with public welfare concerns is not highly valued in students' professional identities as engineers and that this engagement declines over the course of their engineering education.". She attributes this to an engineering 'culture of disengagement'[47], "a constellation of beliefs, meanings, and practices that frame the way profession members conceptualize their professional responsibility to the public"[47], and argues that "Disengagement entails bracketing a variety of concerns not considered directly ''relevant'' to the design or implementation of technological objects and systems, such as socioeconomic inequality, history, and global politics.".[47] She points out that the institutional culture of depolitization actively leads to a disengagement of students with the non-technical aspects of engineering.[48] To counter this, she suggests that "... if engineering programs can dismantle the ideological pillars of disengagement in their local climates, they may foster more engaged engineers.".[47]

In summary, students estranged from the social appear to be funneled by engineering education into a structure where the socio-technical connection is directed exclusively towards profitability, thus leaving no room for innovation directed towards broader problems of the society. This has also led to a concern among scholars of engineering studies and philosophy of technology, that engineering will lose its jurisdiction over technology development, and engineers' role will be that of mere technical consultants, supporting -- instead of leading-- technology design.[49,16] According to Gary Downey[16], "... continuing to place primary emphasis on solving technical problems amounts to accepting a significant reduction in the status and value of engineering work". Particularly given the potential of new engineering design practices that allow an engineer a more autonomous role, Pieter Vermaas[49] warns that, "... if engineering continues to be seen as the discipline that provides technology, design becomes a discipline different to engineering, and engineers will again be forced back into their assistant role by becoming suppliers of technical solutions to other designers.".

Section 2: Design as the focus of educational intervention

The above literature indicates that in order to address the two-fold gap in preparing engineering students for upcoming challenges, an integrated solution needs to be considered. Since engineering design is considered the core process in solving engineering problems or challenges, engineering design education would be the ideal space to provide students the opportunity to integratively apply their knowledge across engineering sciences, mathematics, as well as humanities, social sciences, or ethics. "If accepted on equal footing with the use of models and science, design could serve to moderate the technocratic and instrumental focus that prevails in engineering education."[50] We examine below the canonical design process, taught in the classroom, and some recent approaches that seek to revise engineering design and engineering design education beyond this canonical model. We then analyze a case study of grassroots design, to highlight some issues that are missed by these approaches.

The engineering design process

Dym et al[51] define engineering design as "... a systematic, intelligent process in which designers generate, evaluate, and specify concepts for devices, systems, or processes whose form and function achieve clients' objectives or users' needs while satisfying a specified set of constraints.", and emphasize that "Engineering design thinking and learning are central to the development of an engineer.". Clive Dym[52] and many others have found that experiential learning and project-based learning are the most effective pedagogies for design education, and a careful project selection is critical. David Jonassen[19] recommends problem-based learning as the most suitable instructional methodology for design education, but also points out that course-level implementation has challenges for both students and faculty.

One of the most widely cited schematic depictions of the engineering design process model comes from Pahl and Beitz.[53] Fig. 1 shows a recreated simplified block diagram, based on Pahl and Beitz as depicted by Dubberly.[54]

According to this process model, "In principle, the planning and design process proceeds from the planning and clarification of the task, through the identification of the required functions, the elaboration of principle solutions, the construction of modular structures, to the final documentation of the complete product.".[53]

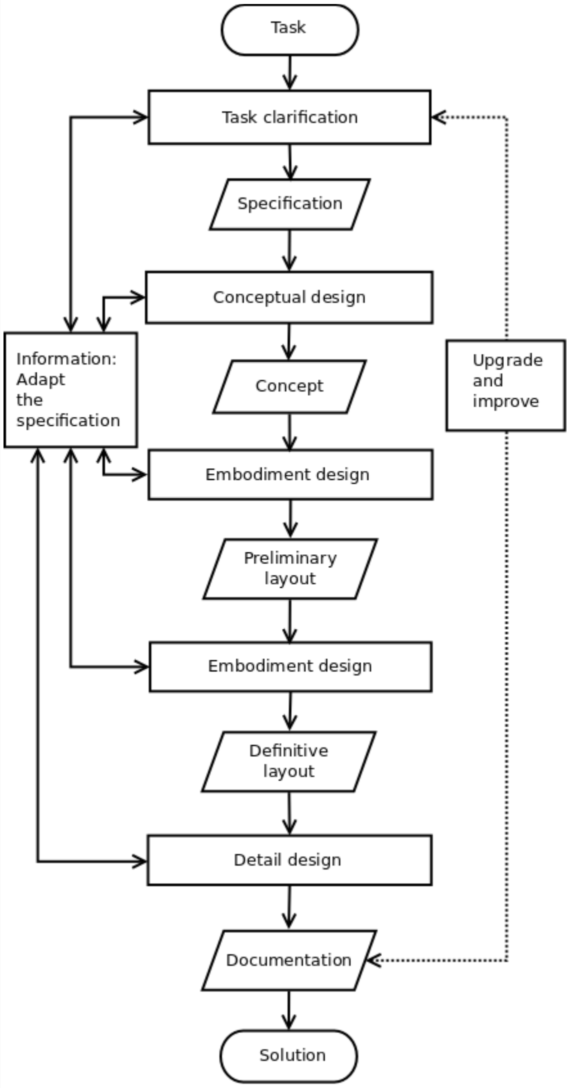

Fig. 1: Engineering design process

Many models[55] of design process have been described and prescribed, depicting a minimum of the following stages:

1. Problem definition / task clarification
2. Conceptual design
3. Embodiment design
4. Detailed design

5. Documentation

According to Haik and Shahin[55], in the conceptual stage “the designer is trying to assess what actions the product should perform during its lifetime and operation.”. They describe the embodiment design stage as where “the product that is being designed begins to take shape. This stage does not include any details yet (no dimensions or tolerances, etc.) but will begin to illustrate a clear definition of a part, how it will look, and how it interfaces with the rest of the parts in the product assembly. This stage is separated from both the conceptual design and the detailed design in that new technologies can replace old ones based on the exact same concept.”.[55] Haik and Shahin[55] comment that “Most engineering degree courses will be within the detailed design stage framework. During this stage, commonly referred to as analysis and simulation, the designer selects the appropriate materials for each part and calculates accurately the dimensions and tolerances of the product.”.

In summary, the task specification stage involves need-identification and problem formulation, and its output may be a list of quantified technical task specifications. The concept design stage focuses on the function while the embodiment design stage decides the form of the machine / technology. In the detailed design stage, the exact technical specifications are worked out. Feedback from each of these stages may result in reconsideration at the previous stages, and in this sense the model captures the iterative nature of the design process.

Critique of the linear model

This linear technical model of the engineering design process has been critiqued and questioned.[19,28,56] Bryan Lawson[57] emphasizes that “It is central to modern thinking about design that problems and solutions are seen as emerging together, rather than one following logically upon the other.” David Jonassen[19] describes design as “... an iterative process of decision making and model building.”. He questions the assumptions in the design process models that design is a predictable process that will result in an optimal solution or that designers perform all the activities in the process. He points out that “During the problem definition stage, engineers analyze constraints in order to develop goals that represent an optimal solution. However, rather than optimizing a solution, designers most often seek to satisfice (Simon, 1955), a strategy that attempts to meet criteria for adequacy, rather than identifying an optimal solution.”.[19]

Mosborg, Adams, Kim, Atman, Turns, and Cardella[58] studied practicing professionals' conceptions of the engineering design process in relation to a design process model synthesized from several introductory engineering textbooks. Even though the block diagram model of engineering design process is critiqued by researchers of engineering practice, Mosborg et al found that, for various likely reasons, of the 19 practicing engineers, only three had major disagreement with the model, while 7 drew alternative types of diagrams.[58] The experts as a whole emphasized problem scoping and communication. They also report that among the 27 statements describing their definition of design, “... the statement most strongly endorsed by the engineers was, “In design, a primary consideration ... is ‘Who will be using the product?’”, while the statement least endorsed was, “Good designers get it right the first time.’”’.[58]

A further comparison of these data with that of students indicated that unlike students, the experts revisited the problem definition stage throughout the design process. “... problem scoping and information gathering are major differences between advanced engineers and students, and important competencies for engineering students to develop.”[59] For analysis, the researchers considered eight activities commonly indicated in the process models of engineering design: problem definition, information gathering, generating alternatives, modeling, feasibility checking, evaluation, decision, and communication.[60] Further support for this practice distinction is provided by a lab study comparing individual designers; the formally trained (m-designers) with the practically experienced (p-designers), on a given mechanical design task.[61] The study found that the m-designers' design process mostly followed the linear process model, and they clarified the task extensively before moving on to conceptual design, while the p-designers did not.

Pahl[51] argues that the knowledge of technical systems or analysis is not sufficient to understand the thought processes that lead to successful synthesis or design, and that studying those thought processes is critical to improving design methodologies. Atman, Eris, McDonnell, Cardella, and Borgford-Parnell[62] explain that the term 'process' is now interpreted broadly, to mean “... an interdisciplinary activity that accounts for the entire product lifecycle in which designers, interacting with stakeholders, identify opportunities; frame goal; generate and test solutions; and plan for the manufacturing, marketing, and servicing of products”. Pieter Vermaas[49] proposes a new 'social design' emerging from new design practices ranging from designer-driven propositional design, designer-guided empathic design, to user-driven participatory design.

A related problem is the understanding of requirements and how it relates to the different design phases. Chakrabarti, Morgenstern, and Knaab[73] define 'requirement' as, “a characteristic which a designer is expected to fulfill through the eventual design”, and point out that “... detailed investigation as to how requirements get identified, clarified and used in the design process and how they influence the quality of its outcome - the emergent design - has not been undertaken before.”. From an analysis of empirical data (protocol study) of four individual experienced (mechanical) designers, Chakrabarti et al[73] report that “if a requirement is insufficiently identified and applied, it is insufficiently fulfilled, and vice-versa.”. They also shed light on some design activities and methods that help or harm the process of requirement identification and application. According to this model of requirement identification and application activities, “... requirements are identified, clarified, detailed and used throughout the design process. However, they are identified mostly during the task clarification phase and increasingly less in the subsequent phases.”.[73]

The linear model and socially engaged engineering

Most of the design studies have been conducted with formally trained engineers and designers, solving standard problems, in lab conditions. As formal practice often 'designs to specifications', these studies do not provide a good sense of socially engaged engineering, particularly how problems/requirements are identified and framed in the social context, or illuminate how design decisions are made, and what values and principles govern them 'in the wild'. In the following case study of socially-engaged engineering practice, we examine the design practice of a formally trained engineering professional while addressing an actual grassroots problem, and analyze how this is different from the linear model.

Section 3: A case study of the design of a rural micro hydro power station

Background

In many parts of the world, villages and hamlets do not have reliable infrastructure for grid power, and the ones that do, receive insufficient and irregular power. Sustained supply of power is particularly challenging in the mountainous regions due to difficulties in installation and maintenance of the grid, and distribution losses. Tough terrain, harsh weather conditions, dispersed and remote population, and poor load characteristics aggravate the cost.

On the other hand, many of these marginalized regions are blessed with natural resources such as near-perennial water streams, wind, and sunlight. Developing decentralized mechanisms for power generation, based on these resources, is a viable technical alternative to centralized grid-based power supply. Micro hydro power stations (in the range of 1-100 KW power) is one such option, a technology known all over the world. In the region where this case study was conducted, traditional water mills existed for centuries, but hydro electricity was generated only towards the end of the 19th century. Government supported the development of micro hydro power stations, along with upgradation of existing traditional water mills for power generation. But many of these stations faced problems, some were abandoned or shut down, and the power problem persists across the geography.

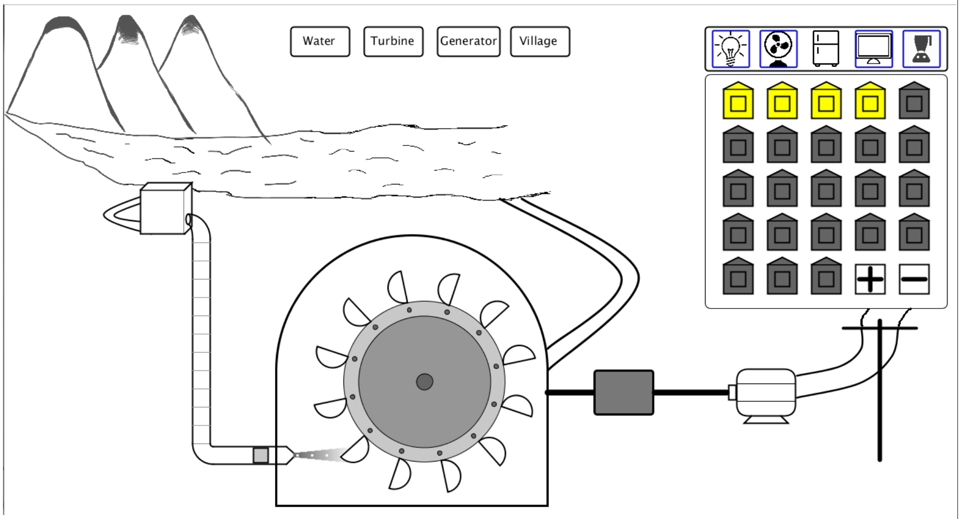

Fig. 2: Micro hydro power generation schematic

Major aspects of design for a micro hydro power station involve sourcing water, designing a turbine and a generator, coupling the turbine with the generator, and distributing the power. The following schematic (Fig. 2) depicts these broad elements. Water from the source may be stored in a tank, and taken to the turbine in pipes. The pipeline may be along a slope, but the 'head' is the vertical distance between the storage and the end of the pipeline where a jet shoots the water on the turbine blades. The head and the flow rate of available water principally govern the theoretical power output from a source of water at any site. These factors also influence the choice of turbine type and the details of turbine design.

Research method

This study is part of a larger study that examines the process of grassroots design, particularly the design of alternate energy solutions. We selected a formally-trained engineering professional (EP) addressing this grassroots problem, to compare with the design process of an untrained designer of micro hydro turbines. (Though we identified two such formally-trained engineers, only one of them (EP) was available, the other having moved out of this domain.) We collected the data through interviews, field observation, and secondary data sources such as project reports. We traced the historical trajectory of design development through this data, and identified some key transitions in the design, across four different sites, over a period of several years. We present these as key design transitions because they appear to be carried into subsequent designs as guiding principles, and are not mere site-specific customizations.

The engineering professional (EP)

EP graduated with a B. Tech degree in Civil Engineering from one of the leading institutes of technology in the country. According to a critique[14], most students from such top institutes aspire to either go abroad for higher education, and/or join 'cushy', high-paying (warm-body) jobs (in multi-national and software companies), that may eventually have little to do with engineering, and sometimes very little connection with the ground realities in the country. Very few enter into profiles that let them innovate or utilize their training to address larger societal problems. EP represents the later.

EP served as a consultant to a state government for eight years, and then worked in the watershed program at a mountain institute. After this he worked with various Non-Governmental Organizations (NGOs), and also started an NGO of his own. During this period, he designed and built around 15 or more micro hydro turbine projects for communities that were deprived of grid-based power supply, in remote interiors of the country.

As he realized after his first project, no trained people, i.e. trained engineers, were “interested in getting into all this”. In addition, EP also used his engineering ability to innovate machines, processes, and products to create more livelihood opportunities for the marginalized mountain people. According to him, micro hydro power, where available, is the cheapest, and the most simple and sustainable mechanism of delivering not only power but also development at the grassroots.

EP's designs and designing process

Four key transition episodes can be identified from EP's designs and designing process for

building micro hydro power stations.
1. Modified water mill
2. Pelton turbine and digital load controller
3. Cross flow turbine and heat sink
4. Electrical and mechanical power

Episode 1: Modified water mill

The situation

In 1975, fresh out of college, EP was asked by one of his professors whether he could develop a power station for a research lab in a non-electrified, high-altitude region of a protected National Park. The professor's team was working on high-altitude plants, and the material they collected got spoiled due to germination by the time they got back to their labs in the city. To avoid this, they needed to set up a lab and conduct experiments where they were collecting the samples. For this they needed electricity, but grid supply did not reach the research site. They needed some other solution, and one major constraint was lack of funds, since the research project had not anticipated need for continuous power at the time of budgeting. Thinking it would be an 'adventure', EP took up the challenge.

The solution

There was a small rivulet flowing near the lab tent, receiving water from seasonal rains, as well as from melting snow that fed it in the summer. The region had traditional water mills installed on such perennial streams. There would be a chute fitted in the stream, to direct the water flow on to the wooden blades of a locally made water wheel, which had a vertical shaft. Excess water would be diverted through a side channel using traditional wooden gates.

EP decided to modify and improve this wheel design and build a micro hydro power station for the research lab. He replaced the straight wooden blades of the turbine wheel with curved ones. Using car spare parts like bearings and axle, he made some small changes to the turbine, and also made it portable. He added a big starter gear and a smaller gear to increase the shaft's rotations per minute (rpm) by ten to twelve times, from 300 to about 3000. This was coupled to an alternator that charged a DC battery. Thus water falling from the chute rotated the turbine and the alternator shaft coupled to it, generating about 700 Watt DC power. This was successfully used to light up the lab tents, and to power electrical equipment such as microscope, camera, and a small incubator.

Afterwards

Though the micro hydro power station on the modified water mill provided enough power for the lab and the resident researchers, in the month of October, when it grew too cold, and many guests arrived, the team did not have enough power to provide warmth or enough ration, so the station had to be closed. But in the process of setting up the station, several key learning points emerged:

- The team realized that many villages don't have electricity and it is easy to generate electricity.

- EP felt “some sense of achievement that it's so easy to do it”.
- Villagers realized that it is so simple to generate electricity from the water they already have.
- EP found that no trained people were “interested in getting into all this”.

These points eventually led to EP's involvement in more micro hydro power generation projects at the grassroots.

Analysis of the design process

From the perspective of the canonical design process, the formal task (specification) can be understood as '*sufficient electrical energy for lab illumination and instruments*'. A rudimentary design concept and embodiment is then identified by EP in the local traditional water mill. Note that this identification jumps ahead in the linear design flow suggested by the canonical model, by connecting an existing resource to the task specification and thus collapsing the function and form - conceptual design and the embodiment design stages - into one. EP modified the mill to improve the rpm as needed, thus also collapsing together the embodiment and detailed design stages.

> “The turbine.. we adapted a local turbine, and we made it ourselves. We made it slightly different, improved version. Actually they were using blades which are straight. If you have curved blades, then you get more impulse, and you get more force from the turbine.”

The turbine is only one part of the solution concept, where mechanical energy is generated from water. This mechanical energy needs to be converted to electrical energy at the required voltage and frequency ratings of electrical devices. Here again, the concept and embodiment was combined, by adapting an existing vehicle alternator. The modified water wheel and the alternator needed to be matched and coupled together, and a gearbox was used for this purpose.

> “... and we had a gear. Gears are there. And then we were using this very good alternator, with that. That used to generate electricity.. with same .. similar system as you have [in] car.” … “Readily available in the market. We.. that also from the disposal market (chuckles). We didn't have money, we couldn't go for.. you know, new and fancy stuff.” “... and it was basically a battery charging system used in the cars only. So this is how we used to run that.”

In this case, the social factors (what activity the electricity should support: a temporary research base that may shift location or wrap up) are embedded in the task specification and cost constraints, which drive the design. Once specified as a task, these social factors influence and constrain the design choices and decisions, but are not explicitly noted as part of the technical design brief. It is possible that the social factors are implicitly considered because EP is part of the academic world that specified the task, and is thus aware of these factors.

Over the following transitions, as EP becomes more experienced in this domain, social factors start becoming explicit factors.

Episode 2: Pelton turbine and a digital control system

The situation

This site was twin tribal villages, in a remote area set in the middle of a reserve forest that was home to wild animals. Grid-based power supply did not reach the 67 households, of about 380 people. In 2005, an NGO working with the marginalized communities in the region since 1979, envisioned a micro hydro power project to solve the power problem of the twin villages. The NGO aimed not only to provide electricity but to ensure inclusion, social and gender equity, and sustainability, in the process. The project was to be implemented with community participation and to be handed over to the community. EP was engaged as a consultant for this project.

The solution

EP designed, fabricated, and built a micro hydro power station near a waterfall about two km from the village.

For this, a Pelton-type turbine was fabricated by EP in his own city. The system was designed to use two alternators, 10 KW and 25 KW each (the potential system outputs for low flow and high flow). To manage the variation in electric load, a Digital Load Controller (DLC) was designed by EP and each house was fitted with the variable load controller with manual reset. Each household got two bulb holders and one tube light, one plug-point, one fuse, and one isolation switch. About ten streetlights were also installed in the village.

Afterwards

A report of the project by the NGO states that the technology was sound, and the power station started providing electricity. Quoting a villager, it says that the "electricity has not only brought practical benefits such as the ability for children to do homework at night or villagers to simply see in their homes after sunset, but also a basic sense of equality with urban people. The electricity has also enabled new community activities.".[63] The report also adds that although it was planned that the project would be handed over to the community for maintenance, this created several glitches. "Unfortunately, no corpus was formed, and no tariff was being collected. The corpus was not collected because initially the project needed to be technology driven in order to meet donor timelines. The timeline did not allow enough emphasis on developing the community's stakes. … No corpus or tariff was collected, leading to community not valuing the system and no fund for future repairs and maintenance."[63]

Analysis of the design process

Again, the formal task (specification) can be understood as: '*sufficient electrical energy for a village having a water source with high head but also a high seasonal variation in flow. This includes community participation as labor during construction, and as payers and managers of the service later on.*'

The technical choice of a Pelton type turbine and a DLC takes into account the technical parameters, maximizes the opportunity in high head water source, and compensates for water flow variation and load variation.

In the case of the turbine, the characteristics of the local water source indicated two technical choices for the type of turbine at the embodiment design stage. Either a 'pump as turbine' or a Pelton wheel. The 'pump as turbine' is less expensive and widely available. But it can accommodate only one flow rate and its efficiency is low. A Pelton wheel on the other hand can handle variations in flow and high head.

> "It had a very nice waterfall actually, coming from 100m. 100M fall is a very good fall actually. … And we had a very nice Pelton wheel, very nice one. And which could run with very small amounts of water."

EP chose the Pelton wheel, designed and fabricated it meticulously in his city, and took it to the site.

The other issue is to regulate the generator output frequency in case of variable load, such as during night and day, in a village.

> "I happened to have some problems with the control systems. So control was the main problem actually those days for me. … Actually what happens is, in a power station, suppose you are generating 40 KW power, and you .. you utilize just 5KW..."

When the generator load drops like this, to maintain the generator output frequency constant at the required frequency rating, the turbine rpm needs to be held constant, and not allowed to run away. This could be done by proportionately varying the impinging water by controlling the water flow. But automatic varying of jet diameter would involve mechanical power and a feedback system to trigger it.

> ".. the water control is actually by moving the valve. Valves require a lot of power for movement."

In order to avoid this, EP opted to manage the load drop using a digital load controller.

On the other hand, digital technology may need a trained and equipped person for its maintenance, troubleshooting, or repairs, and this may be expensive or not readily available. This constraint / requirement remained implicit, unarticulated, and thus unmet, in the conceptual and embodiment design stages.

As the Pelton turbine was fabricated in the city, the community had no experience of handling technical issues related to it, even though the NGO had intended for the maintenance to be handled by the community. In later projects, the NGO emphasized training local people to fabricate the turbines locally.

Social factors remained externalized in the task specification and were not explicitly a part of the technical design. As a result, though electricity was generated, the community did not own the project enough to create a corpus fund for maintenance. Eventually the NGO had to recommend halting the power generation till this issue was addressed.

Episode 3: Cross flow turbine and heat sink

The situation

Even in a typical remote mountain village, high water head may not always be available. For low head situations, if the discharge is also low or seasonally variable, then the jet diameter needs to be large. As a result, the runner diameter needs to be large, and a Pelton turbine becomes too big. Alternately there need to be multiple jets. Also, both the Pelton turbine and the digital load controller are too expensive, complicated to manufacture, and difficult to maintain. Repair services are not locally available.

> “So if you use these kind of technologies [not audible] more and more complicated. And the capability in rural area is not you know such that you are able to take care of complicated technologies... And similarly control systems are again all electronics based control systems. Something goes wrong in control system, you are in trouble, you have to go down [to the plains].”

The solution

EP replaced the Pelton-type turbine in his designs with a cross flow turbine. Nearly the same returns can be derived by using a cross flow turbine, also known as Banki or Ossberger turbine, which is simpler to design, fabricate, and maintain.

'In low-head installations, maintenance and mechanism costs often become important. A low-head system moves larger amounts of water, and is more likely to encounter surface debris. For this reason a Banki turbine also called Ossberger turbine, a pressurized self-cleaning crossflow waterwheel, is often preferred for low-head microhydropower systems. Though less efficient, its simpler structure is less expensive than other low-head turbines of the same capacity. Since the water flows in, then out of it, it cleans itself and is less prone to jam with debris.'[64]

EP also replaced the DLC in his designs with a heat sink. A heater is immersed in water, which gets heated, and can be used or let out, thus protecting the system and keeping the output frequency constant.

> “There's a frequency sensor. If it is 50 (Hz), it's ok. If it crosses 50, that means there's surplus power in the line. So automatically some switches get opened, and some heaters get on.” “So water.. water is wasted, but your power station is safe.” “So the principle is same here as well.. it senses the frequency, and it will actuate the valve...”

Analysis of the design process

EP's conceptual and embodiment design in this case takes into account the constraints imposed by the social and environmental factors, alters the technical choices, and offers a technical solution. The task specification itself *includes the social constraint of locally available technical capabilities*.

Embodiment of the concept for turbine is modified from Pelton to a less efficient but simple-structure and low-cost cross flow turbine. The self-cleaning feature adjusts technology to the level of the technical challenge in the local context.

> "You see, you can run up to four meters.. you can very easily run your cross flow turbines. There is no problem in that."

Instead of a digital load controller, EP decided to a simple heat sink in the form of a heating coil. Adapting a simple heating coil to act as a substitute load modifies and combines the conceptual and embodiment design stages for load control. It ensures safety at a lower cost, complexity, and maintenance, although at some loss of power.

Further, the overall cost is under control, even at the scale of micro power. It need not be scaled up to a mega power station level to reduce the costs.

> "If you make it very sophisticated.. the micro one, and add many things to it, then it becomes expensive, otherwise it's not expensive." "It's a misconception that micro power stations are very expensive. This is a lobby that is afraid of the micro-hydro producers."

Episode 4: Electrical and mechanical power generation

<u>The situation</u>

The renewable energy ministry, along with international funding agencies, implemented a power supply project in remote villages around 2006-9. It aimed to demonstrate how renewable sources of energy can reduce poverty through improved quality of life and increased livelihood opportunities in remote, non-electrified villages that are not likely to get electricity from the grid.[65]

EP's NGO was an implementation partner for the project in a remote mountain district, based on their track record in micro hydel and in community based, innovative, low cost engineering solutions in difficult locations.[65]

<u>The solution</u>

Based on the water source, EP designed a system of two turbines running side by side: one turbine for electricity generation, and another turbine for motive power application when no electricity generation was required. Further, EP designed scaled-down machinery running on motive power, for livelihood generation based on local natural resources.

"Trained grassroots engineers were involved in all the fabrication and construction activities and only local labour (in and around the village) was used. Two sheds have been constructed, one for electrical power generation and the other for mechanical power generation so that machinery for daily use is independent and does not require electricity. In case of electrical faults, running of machinery is not affected."[65]

"The project has the capacity to generate livelihoods and income earning opportunities for a large number of men and women through wool washing, wool carding, spinning, oil milling, flour milling and rice threshing for all those willing to learn to run the machine. The project will reduce drudgery for all households using the flour mill, oil expeller and rice huller in the village ..."[65]

Afterwards

EP's most recent project is conceived on the model of the Renewable Energy for Rural Livelihoods (RERL) project with some modifications. Six villagers, one of them an owner of a traditional water mill constructed by his grandfather, have formed a group. Utilizing the electrical and mechanical power generated by the micro-hydro power station, they plan to run businesses that will offer various products and services to the villagers and passers-by. They have formed a committee, and opened a joint bank account to keep aside a corpus for maintenance of the system.

Analysis of the design process

EP's conceptual and embodiment design takes into account the constraints imposed by the social and environmental factors, *alters the technical choices*, and offers a technical solution.

> "... there are two things actually in this .. whether you want speed or you want power at low speed. .. "
> "... after doing the [not audible] project it was a very big realization that unless people are making money out of that, you can never run this power station. But if they are able to make money out of it, it is the best scheme actually."

Some of the social and environmental factors now get explicitly stated in the task specification, for example building the technical expertise of the local people, designing for easy maintenance and repairs, and running machines that support livelihood activities like wool carding.

> "... we should make equipment in such a way that can be opened easily. So there had to be some change in it. Every time we used to think which part umm, you know, is difficult to remove, and simplify it actually... "
> "... If you are able to provide electricity to one village, it's a great thing. If you're able to provide livelihoods to the people with electricity, it's the greatest thing."

Findings from the study

"There are those who choose the swampy lowlands. They deliberately involve themselves in messy but crucially important problems and, when asked to describe their methods of inquiry,

they speak of experience, trial and error, intuition, and muddling through."[66]

This historical analysis of some of the key transitions in EP's design process indicates an increasingly explicit understanding of social factors, and the connection between society and technology, and an explicit incorporation of these into the design process. According to EP,

> "Now if a village comes to me for a micro power station, I insist for a livelihood component if they want me to accept the project ... if you provide technology that gives you returns, so people will also be able to give you some, you know, good returns that way. So we never used to think like that earlier. It was just electricity." "The toughest part is community, and the livelihoods actually .. it is the toughest part in this."

In comparison with the formal textbook model, we note that:

1. Within a design episode, EP's design process is not linear. It jumps ahead – and skips or combines stages. This is similar to results from other studies of practice. As David Jonassen[19] describes, "... designers seldom perform all of the activities defined by normative design processes".
2. EP engages with the design process in context, and various social and environmental factors influence various stages of EP's design process. This interaction is not limited to only an initial task specification stage, which once frozen, would as per textbook be expected to disconnect / disengage from the context during the rest of the design process.
3. Across design episodes, the social, environmental, and material factors go from being embedded and implicit to being progressively explicit to EP. In this process, EP reformulates the broader need definition or the problem space in the subsequent episode. The social factors are explicitly stated in the task specifications. This reflective feedback across similar design problems is not captured in the textbook design process, even though it depicts a within-episode iterative feedback loop.
4. The reformulated need / problem guides the design decisions at all stages of the design process, and this results in rethinking the entire solution, as well as reforming the guiding principles. It is not a process of refitting the previous solution by tweaking only the detailed design.
5. In EP's design process, the kind of detailed design calculations (use of engineering knowledge) called for depends on the design decisions of the earlier stages; and is not as direct / obvious as in a textbook problem with given technical parameters.
6. Engineering is a socio-technical enterprise. The necessary interaction between the social and technical is not reflected in the textbook design process. Task specifications may actually work as a mechanism to externalize the social factors from the engineering problem space.

The following salient points emerge from this case study:

- Particularly in the case of grassroots needs, the problem definition or understanding the requirements is very complex, and the needs are not always explicitly stated or directly technical. The material and social structures interact with the technical. In the process, the needs and constraints emerge clearly.

- EP's key design changes are interconnected in his person. His explicit design preferences in the reformulated task specifications are a coagulation of his experience of addressing complex grassroots problems. Students, unless trained, may take many years to understand the need and method to do this, if at all.

- There can be many possible technical designs and no single correct answer or solution. In this sense, the connection between product/technology and society is actually fluid or plastic. But this plasticity is available only if the designer begins at the need / problem definition stage. (Where problem definition requires answering questions beyond the technical or material, like who is it a problem for, who benefits in what way, who loses.. why, who invests, who spends.. and so on.)

- This plasticity of the socio-technical connection is not available to engineering students if they are groomed for (and with) mainly the detailed design, and to some extent conceptual and embodiment design education, but lack the skills for need / problem identification and definition.

Section 4: Discussion

As the social needs of marginalized areas do not fit / map on to the dominant / mainstream technological and business practices, these problems are largely ignored by the world of technology, business, and governments. Such problems are usually addressed by rural innovators, and Anil Gupta (National Innovation Foundation, SRISHTI, and Honeybee Network) organizes walkathons twice a year in search of 'grassroots innovators' who address such problems. He comments, “There are problems in our society that we have decided to live with almost indefinitely. The result is a feeling of alienation among the affected people.”.[67]

It is worth noting that trained engineers and engineering students live in these areas, but they either do not see the problems, or do not know how to address them. Contrast this with doctors serving in rural areas, and lawyers doing pro-bono work. The lack of equivalent socially engaged identities in engineering, we contend, is an outcome of not including real life need/problem formulation and need/problem framing in the engineering education curriculum. Case studies, which can provide insight into real world issues, are central components of training in medicine and law, but no longer a core part of engineering.[68,69,70]

As discussed in section 1, the need for a socio-technical understanding of messy, real-world engineering is recognized, but the way forward is not clear. Gary Downey[16] poses the questions – “Might the main challenge facing the making of engineers in the present be to re-imagine and re-define in its entirety the obligatory core and essential heart of engineering identities?” and “Could engineers be for more things if an image of engineering as problem definition and solution successfully gained substantial acceptance across schools of engineering?”.

The case study of EP outlines a way of generating such an image -- an inspiring instance of an engineer who engages with a neglected problem of the marginalized areas, and develops alternative solutions. In the case of EP, this is a (reflection-in-action) process that takes place over a number of years and projects, and this leads to the engineer redefining the need/problem specifications differently from the merely technical specifications. Such flexibility exists in the society-technology connection, and this provides the space for new technology innovations that address the unmet basic needs in a society.

In the currently dominant centralized revenue model, the social structure of the business world directs the social-technical connection in one specific way – towards profit and its operationalization using economies of scale. This bias, a feature of the corporate social structure, restricts the design space – the direction of exploration for solutions -- to 'within' the detailed design phase of the design (problem-solving) process. EP, not thus restricted, is able to go back to the problem definition iteratively and this process leads to the emergence of innovative solutions that fit the problems, as opposed to solutions developed outside the social and environmental context, which seek 'idealized' problems. EP uses formal engineering knowledge for detailed design calculations depending on the design decisions formed at the earlier stages; and not the other way round.

A perspective rooted in the centralized revenue model would consider EP as 'customizing' a core engineering solution, which optimizes performance. However, this view considers the centralized revenue model, and optimality based on profit, as normative. The key point about EP's design process is that his notion of optimality evolves to include social and environmental factors. This shift goes beyond customization, as it rejects the optimality assumed by the centralized revenue model. One central insight from this analysis is that optimality based exclusively on performance acts as a gateway and stand-in for a value system, where profit is the central design norm and virtue, and other notions of optimality are aberrations. Training for performance optimality thus is the same as training for profit, which becomes the only value and norm. This is clearly not what engineering education ought to be doing, particularly now that sustainability is a key engineering norm. This type of training blinds engineers to wider design possibilities, and works as an implicit device for capturing/directing the work force towards socio-technical structures that are unsustainable.

According to Gary Downey, students taught to solve problems in idealized conditions would lack the skills to do such 'wide' design. In proposing an alternate image of engineering as Problem Definition and Solution (PDS) Downey[16] also recommends practices of “early involvement in problem definition, collaboration with those who define problems differently, assessing alternative implications for stakeholders, and leadership through technical mediation.”. According to him, “The key point here is that engineers trained to integrate problem definition into mathematical problem solving would involve themselves early in processes of problem solving, prior to the point at which a clear design problem emerges or can be claimed.”.[16]

Pieter Vermaas[49] comments that, “This inclusion of the formulation of the needs in design practice can take different forms and creates a spectrum of design practices.”. He too adds that training engineering students for these forms of design will enable them to venture beyond “their traditional assisting role of providing technical solutions to problems as defined by these companies and their managers", and to "start doing design outside the immediate context of commercial companies, for users, for developing countries, for society or for the environment.".[49]

Conclusion

Donald Schon[66] emphasizes that, "Problem-setting is a process in which, interactively, we *name* the things to which we will attend and *frame* the context in which we will attend to them." (italics original). "A conflict of ends cannot be resolved by the use of techniques derived from applied research. It is rather through the non-technical process of framing the problematic situation that we may organize and clarify both the ends to be achieved and the possible means of achieving them."[66]

However, such a process of framing is not discussed in the engineering curriculum, say for example when discussing the theory for power generation, or alternate energy technologies. Learning of these, if at all, happens either implicitly, or later, on the job.[71,50] Unfortunately, few students are likely to venture down this path, as they do not know that it exists, or do not have the training to navigate it. Possibly, their image of engineering and identity as an 'engineer' also limits their perspective, making them consider such problems as not 'their' job.

Problem formulation training is not an explicit, formal, and planned area of engineering design education. There are a few specific research studies (for example, studies from decision making domain), and rare educational initiatives such as Rensselaer Polytechnic Institute's Programs in Design and Innovation,[72] (or the Design and Innovation program at the Technical University of Denmark, the Engineering Design program at Delft University of Technology, and the new Sustainable Design program at Aalborg University[50]) focusing particularly on the problem formulation mechanisms in the context of complex and ill-structured real-world problems, and on teaching and learning these competencies.

We believe that the formal inclusion of problem formulation training in EE, particularly using case studies of actual socially engaged engineering practice, would allow students to experience this key aspect of engineering design, and understand the fluid and plastic connection between society and technology. The study we report begins the process of documenting case studies of grassroots designers, and understanding such practice in its formal and informal context, which we believe offers a possible way of introducing this plastic connection into engineering education.

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