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Beyond Efficiency: Engineering for Sustainability Requires Solving for Pattern

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ABSTRACT
There is a consensus that engineering design practice and education needs to change, to address the sustainability challenges facing the planet. This shift towards sustainability engineering requires illustrating successful design practices that embed sustainability values, particularly designs that move away from the current focus on input–output efficiency, towards eco-social and socio-technical approaches to design. We present three cases where the designs illustrate such a widening of the design space, to include parameters beyond input–output efficiency and optimization for profit, and leading to innovative socio-technical solutions. These cases suggest that the socio-technical connection is highly plastic, allowing for a range of ways in which the ecological, social, and technical could come together to form innovative and sustainable solutions. They illustrate a novel design principle – 'Solving for Pattern' – where the designs seek to address many problems simultaneously in an interconnected way. These cases indicate that designing for sustainability requires a broadening of the roles and identities of engineering designers, to include themes wider than engineering sciences and mathematics. Including these and similar case studies in engineering curricula could support the shift towards such a broader engineering design identity, where sustainability is a key component of design practice.

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1. Introduction

> The things we call 'technologies' are ways of building order in our world. . . . For that reason the same careful attention one would give to the rules, roles, and relationships of politics must also be given to such things as the building of highways, the creation of television networks, and the tailoring of seemingly insignificant features on new machines. The issues that divide or unite people in society are settled not only in the institutions and practices of politics proper, but also, and less obviously, in tangible arrangements of steel and concrete, wires and semiconductors, nuts and bolts.[1]

Human activity, driven by science and technology, has built a new artificial world, damaging the planet's ecosystem significantly in the process. Systemic changes resulting from

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[1] Winner, *The Whale and the Reactor*, 2010, p. 29.

this activity, such as global climate change and poverty, are now central concerns while designing future policies and technologies that promote sustainability. The need to shift to sustainability-oriented design has led to significant introspection within the engineering community,[2] with the recognition that engineering practice needs to change, particularly to take responsibility for reducing hazardous side effects of engineering products and processes, such as pollution and global warming. This change requires changing the way engineering products and processes are designed, particularly to change design practice such that environmental and social sustainability are key requirements. This shift, in turn, requires a broadening of the engineering identity, and the way twenty-first-century engineers are trained. To this end, several reforms in Engineering Education have been envisioned.[3]

At the policy level, Accreditation Board of Engineering and Technology[4] (ABET) has revised its outcomes of engineering education in EC 2000, to list as one of the hard skills to be learned: 'an ability to design a system, component, or process to meet desired needs within realistic constraints such as economic, environmental, social, political, ethical, health and safety, manufacturability, and sustainability (3.c)'. Institution of Engineers, Australia, updated the procedure for accreditation of the engineering baccalaureate to ensure inclusion of sustainability learning.[5]

This shift in focus has motivated various efforts to include sustainability into various degree curricula, pedagogy, and assessment. For example, a 'light' version of the participatory 'backcasting' course was provided by Quist, Rammelt, Overschie, and Gertjan de Werk,[6] where students were introduced to the backcasting method of defining a desirable future and then working backwards to identify policies and programs that will connect the future to the present. Research studies have tracked the effects of such interventions. For example, in a study examining student understanding of the concept and complexity of sustainability, Carew and Mitchell[7] found that 'academics may need to construct sustainability teaching and learning which allows students to focus initially on preferred areas of sustainability learning prior to, or as a means of, exploring sustainability's breadth and depth'. Huntzinger, Hutchins, Gierke, and Sutherland[8] reviewed some selected university website content (course, pedagogy, and assessment details) to study the nature of integration of 'sustainability' and 'problem-based learning' in the engineering curriculum. Segalàs, Ferrer-Balas, Svanstrom, Lundqvist, and Mulder[9] collated the desired sustainability competences for engineering bachelor graduates in some parts of Europe. Chau[10] studied the integration of sustainability concepts into an undergraduate civil engineering curriculum in Hong Kong, and found that these students were rated better by prospective employers, compared to other colleges with similar programs but without sustainability studies.

2 UNESCO, "Engineering: Issues, Challenges, and Opportunities for Development," 2010.
3 NKC, "Report of Working Group on Engineering Education," 2008; RAE, "Educating Engineers for the 21st Century," 2007; NAE, "Educating the Engineer of 2020," 2005.
4 ABET, "Criteria for Accrediting Engineering Programs," 2011.
5 IEAUST, "Manual for the Accreditation of Professional Engineering Programs," 1999.
6 Quist et al., "Backcasting for Sustainability in Engineering Education," 2006.
7 Carew and Mitchell, "Characterizing Undergraduate Engineering Students' Understanding of Sustainability," 2002.
8 Huntzinger et al., "Enabling Sustainable Thinking in Undergraduate Engineering Education," 2007.
9 Segelàs et al., "What Has to Be Learnt for Sustainability?" 2009.
10 Chau, "Incorporation of Sustainability Concepts into a Civil Engineering Curriculum," 2007.

Many pedagogical interventions have tried to address the problem of building sustainability values. Chau[11] highlighted a team-based design project with problem-based learning approach as an effective method, suggesting that multidisciplinary skills developed during the learning process might contribute significantly to developing knowledge on sustainability. According to McLaughlan,[12]

> focus on learning strategies is necessary to create the integrated and interdisciplinary perspective required for sustainability education. Active learning strategies, which use methods that can accommodate conceptually and practically diverse data and divergent epistemologies are needed. Role-play-simulation, online debates and scenario building are active, participatory instructional strategies.

Feisel and Rosa[13] looked at the role of instructional laboratories in providing exposure to real-world problems, considering the 'lab as a place to have some contact with nature, whether real or virtual'. From a different direction, Chandrasekharan and Tovey[14] suggest that ' . . . most of our universities have engineering schools that are focused on assembling and manufacturing complex artifacts, a valued and respected activity. A plausible institutional change would be to develop deconstruction/re-usability engineering departments within these engineering departments'. Shuman, Besterfield-Sacre, and McGourty[15] cite a number of successful and promising interventions, such as internships in foreign countries, international collaborations among academic institutions and non-governmental organizations (NGOs) to expose students to social problems and stress on learning a second language, and critical study of international development, regional focus, and humanities as a part of engineering coursework. A study of students' response to a sustainable design challenge stressed the need for a pedagogical model that helps develop students as professionals, which is different from a standard instructor-led learning model.[16]

These efforts to reform engineering education towards sustainability have led to some changes. However, research and critique from the domains of history, philosophy, sociology, politics, and practice of engineering and technology suggests that these changes are not sufficient, because they do not seek to reform foundational assumptions, particularly moving to the understanding of engineering as a socio-technical enterprise.[17] Feenberg[18] argues that technical disciplines are fundamentally oriented towards creating efficient functional devices, and this process leads to systematically abstracting away social dimensions of the activities, which are then considered to be addressed by the humanistic disciplines. This focus on functional and technical efficiency gets augmented by the notion of economic efficiency, and the focus on techno-economic efficiency has become the default engineering perspective of the mainstream industry. In the process of achieving techno-economic efficiency, the abstracted socio-ecological components are neglected or sacrificed. Engineering education has followed and institutionalized this dichotomy

[11] Chau, "Incorporation of Sustainability Concepts into a Civil Engineering Curriculum," 2007.
[12] McLaughlan, "Instructional Strategies to Educate for Sustainability in Technology Assessment," 2007.
[13] Feisel and Rosa, "The Role of the Laboratory in Undergraduate Engineering Education," 2005.
[14] Chandrasekharan and Tovey, "Sum, Quorum, Tether," 2012.
[15] Shuman, Besterfield-Sacre, and McGourty, "The ABET 'Professional Skills,'" 2005.
[16] Mann, Radcliffe, and Dall'Alba, "Using Phenomenography to Investigate Different Ways of Experiencing Sustainable Design," 2007.
[17] Stevens, Johri, and O'Connor, "Professional Engineering Work," 2015; Vermaas et al., "A Philosophy of Technology," 2011; Faulkner, "Nuts and Bolts and People," 2007; Vinck, *Everyday Engineering*, 2003; Suchman, "Organizing Alignment," 2000; Hughes, "The Evolution of Large Technological Systems," 1987; Law, "Technology and Heterogeneous Engineering," 1987.
[18] Feenberg, *Transforming Technology*, 2002.

between the social and the technical, prioritizing techno-economic efficiency in design, and neglecting the social and ecological. This raises the challenge of integrating these left out components with the technical core of engineering.[19] This is a central requirement to address sustainability problems, which span the technical, social and ecological domains in complex and messy ways.

Engineering Education Research, particularly engineering design education research, indicates a two-fold gap that needs to be addressed to meet the integration challenge:

(1) Engineering graduates are technology-centered, and highly disengaged from the socio-political aspects of engineering.[20]
(2) Engineering graduates are not trained to situate themselves in problem contexts, particularly 'wicked' real-world contexts, to independently frame problem requirements.[21]

Study and analysis of successful cases of designing for sustainability could be a good starting point to bridge this gap. While textbook cases of formal practice capture the design process driven by formal methods that 'design to specifications', we explore here three selected cases of design in the 'wild',[22] to understand the way they contribute to sustainability, and the larger questions they raise about current engineering practice. They shed light on the limitations of techno-scientific, theory-driven, and socially disengaged approach to design. They also present contrast cases to understand alternate ways of approaching design problems, to innovate for sustainability. In analyzing these cases, we discuss how the current technology-centric idea of efficiency needs to be broadened, to develop an ecological and socio-technical approach to efficiency, which takes into account a network of multiple factors to 'solve for pattern'.[23]

The term 'Solving for Pattern' comes from philosopher and farmer Wendell Berry, who highlights that things are embedded and interconnected in the world, and any modifications (such as new technology) restructure these patterns, which makes it necessary that designing requires keeping the larger patterns in mind. In explaining the limitations of 'techno-economic efficiency driven' singular best solutions, Berry says,

> A bad solution solves for a single purpose or goal, such as increased production. And it is typical of such solutions that they achieve stupendous increases in production at exorbitant biological and social costs. A good solution is good because it is in harmony with those larger patterns – . . . It is the nature of any organic pattern to be contained within a larger one. And so a good solution in one pattern preserves the integrity of the pattern that contains it.[24]

[19] Downey, "PDS: Engineering as Problem Definition and Solution," 2015; Trevelyan, "Engineering Education Requires a Better Model of Engineering Practice," 2009; Bucciarelli, "Designing Engineers," 1994.
[20] Canney, Bielefeldt, and Russu, "Which Courses Influence Engineering Students' Views of Social Responsibility?" 2015; Cech, "Depoliticization and the Structure of Engineering Education," 2015; Canney, Bowling, and Bielefeldt, "In Their Own Words," 2013; Cech, "Culture of Disengagement in Engineering Education?" 2013; Rugarcia et al., "The Future of Engineering Education I," 2000; Felder et al., "The Future of Engineering Education II," 2000; Petrina, "The Political Ecology of Design and Technology Education," 2000.
[21] Jonassen, "Engineers as Problem Solvers," 2014; Huntzinger et al., "Enabling Sustainable Thinking in Undergraduate Engineering Education," 2007; Dym et al., "Engineering Design Thinking, Teaching, and Learning," 2005; Schon, "The Reflective Practitioner," 1984.
[22] Hutchins, *Cognition in the Wild*, 1995.
[23] Berry, "Solving for Pattern," 1981.
[24] Berry, "Solving for Pattern," 1981.

The case studies we present embed this design principle, and we propose that integrating such design case studies in engineering curricula would be an effective way to enrich the pedagogical model, in ways that every student would seek to, and would be able to, design for sustainability and solve for pattern.

The paper is structured as follows. In Sections 2, 3, and 4, we present three cases of engineering design and their analyses. The first case is the design of a low-cost sanitary napkin making machine by AM, a non-formally trained school dropout (Section 2). The second is the design of micro hydro power systems for remote interiors by EP, a formally trained engineering professional (Section 3). The third case is the design of Danish wind turbines, by a network of nonacademic engineers, technicians, and artisans in Denmark (Section 4). In Section 5, we discuss how these cases collectively demonstrate the plasticity and diversity of socio-technical connections and a 'Solving for Pattern' approach. We conclude with a discussion of how these cases, and other similar ones, call for a design thinking beyond techno-economic efficiency, and their implications for the formation of a new engineering identity beyond formal knowledge that is needed to engineer for sustainability.

2. AM's sanitary napkin making machine

AM, a school- dropout from Coimbatore, India, was selected as a 'Pioneer' and one of 'the hundred most influential people in the world' in 2014 by *Time* magazine.[25] The recognition was in honor of his grassroots innovation, a set of four semi-automatic machines to manufacture sanitary napkins. AM's machines cost about 75,000 Indian Rupees (INR), are easy to operate,[26] and the design is provided as open source. Commercial automatic machines, on the other hand, cost 25–30 million INR, are designed for industrial use, and the technology is patented. With AM's machines, a sanitary napkin costs between one and two INR a piece (about 50 napkins for a US dollar). Before AM developed his machines that manufacture low-cost napkins, branded napkins available in the market (made by multinational companies) cost about 10 INR a piece, and were not affordable for most women in the low-income strata. AM's design has allowed self-help groups in many countries across the globe to manufacture their own low-cost napkins. He is currently experimenting with organic material and disposal options, to make the napkin a biodegradable product.

AM has studied formally only up to high school, and dropped out of school to work in various trades, including as a helper in workshops, to support his mother, sisters, and wife. Apart from this hardship, he had to struggle hard against social attitudes to develop the innovative machine. In researching menstruation – a taboo subject in India – he faced ridicule and rejection, and was almost ostracized by his village community, before his innovation won national and international acclaim.

He initially developed napkins, and once this technology was perfected, he moved to developing machines that make napkins. Even though he had the option of making napkins and selling them at a high profit, he chose instead to manufacture the machines he designed, and sell the machines at a minimal profit to women's self-help groups, who could then set up their own napkin manufacturing businesses. Currently, more than 600 machines

[25] Gupta, *Arunachalam Muruganantham*, 2014.
[26] National Innovation Foundation, *Mini Sanitary Napkin Making Machine*, 2014.

made by his startup company, Jayaashree Industries, are installed across 23 provinces in India.

Despite numerous offers, AM refuses to sell his innovation to the corporate world. 'I didn't take the money route because I saw my parents struggle for survival', he explains. 'I knew that this machine could provide a sustainable livelihood for many rural women.'[27] The women are able to offer a low-priced product as well as generate wealth. These women at the grassroots (the low-income strata) of the society find gainful employment in their own neighborhood, and at the same time create awareness about sanitary hygiene.

> Shops are usually run by men, which can put women off. And when customers get them from women they know, they can also acquire important information on how to use them. Purchasers may not even need any money – many women barter for onions and potatoes.[28]

AM's innovation has thus created a 'revolution' in public health and women empowerment at the grassroots level, and significantly disrupted the napkin business. It has forced major napkin manufacturing brands to bring out low-cost products, and they now compete with women's self-help groups to grab a share of the low-income market.

AM's design is thus a solution that addresses not only the technical aspects of providing low-cost sanitary napkins. It also addresses social, cultural, economic, and ecological aspects of the complex problem of women's menstrual hygiene. Productivity and empowerment of women are embedded in his design. His solution is much more innovative because it solves for long-term equity and sustainability, rather than short-term profit-making. Even though it does not resolve the problem of sanitary waste generation (yet), his solution is close to being a case of 'Solving for Pattern'.[29]

2.1. Analysis of AM's designing

Current technology design is often driven by engineering sciences and mathematics, which creates a problem space where the needs or requirements that could be addressed by the technology are still unknown, or are hidden. In this design approach, the need for the technology is often 'created' in the society, after a technological innovation is developed. The focus on innovations of this kind, where the socio-technical connection is established after the design of the technology, has led to many existing needs in the society remaining unaddressed. This approach to establishing the socio-technical connection has unfortunately become the default design model, and engineering education has changed to accommodate this profit-focused model, emphasizing engineering sciences and mathematics alone in their curricula.

AM's technology design provides an important contrast model, illustrating an alternate socio-technical connection. His technology design starts from a social-economic need, and includes many socio-cultural parameters beyond efficiency in the framing/scoping of the problem. This creates a wider design space, where a novel and disruptive design solution is found. A focus on merely the techno-scientific aspects of the design would consider his problem already solved, and would thus miss his disruptive innovation.

[27] Sandhana, *India's Women Given Low-Cost Route to Sanitary Protection*, 2012.
[28] Venema, *The Indian Sanitary Pad Revolutionary*, 2014.
[29] Berry, "Solving for Pattern," 1981.

Many aspects of his design and design process illustrate this alternate socio-technical connection and 'Solving for Pattern'.

(1) An important aspect is the identification and a deep understanding of the 'need' in its socio-economic and environmental context. AM did not venture into the sanitary napkin innovation as a result of some scientific breakthrough that could be applied to this segment, or because there was a good market for the product. He was drawn to the problem of women's sanitary hygiene out of empathy for his wife and sisters, who could not afford the branded sanitary napkins, and were forced to use unhygienic options. This is a case across the globe for most women in the low-income strata. They need access to a low-priced product, but no company is interested in making one. AM, believing that the napkin is made of cotton, and is being sold at about 40 times its price, set about designing napkins that could be made and sold at a lower price.
AM's design process also demonstrates the length to which a motivated designer would go to really understand the need, and to test the way the solution fits the need. AM initially requested his wife and sisters, and later some medical students, to try and give him feedback about the napkins he designed. But when their response waned, he became 'the man who wore a sanitary pad'. He actually wore a football bladder filled with goat blood to understand the menstrual flow and its absorption in his sanitary napkin. The experience led him to wonder how women handled the inconvenience every day, when one could not work as usual even with a running nose.

(2) It is worth noting how AM's design, starting from grassroots requirements (low cost, women's health, livelihood, empowerment), radically disrupts standard distinctions between requirements, specifications, product design, and manufacturing design. In most cases of innovation, the product design is the primary innovation, and the design of the manufacturing machine is treated as a scaling and optimization problem. Since the manufacturing machine almost always functions within a profit framework, the design of the machine is based solely on input–output efficiency, and thus functions also as a proxy system for generating profit. The separation of the product design and manufacturing design processes allows profit to dominate the design once the product is developed. Since AM's design started from requirements, and went all the way to manufacturing, he could combine the two design processes (product and manufacturing), and come up with a more sustainable and equitable, not to mention disruptive, design. Standard engineering practice, and curricula, rarely provide situations where designers move all the way from gathering requirements to developing specifications to product design and manufacturing design. In most situations, requirements are identified by one group (the 'innovators') and they translate these requirements into technical specifications, based on the standard business and socio-technical frameworks, which are oriented towards profit. Engineers then work with this technical specification as the target for design. AM's case illustrates that the design space is not limited to these technical specifications.

(3) Another aspect of AM's design is that his machines are semi-automatic.

> The towel-making machine transforms cellulose into sterilised towels in a four-part process. In the first stage, it chops up wood using a powerful motor. Then the operator compresses the pulp manually into a towel shape by controlling a core-forming unit with a foot pedal. They wrap each towel with a non-woven fabric and seal them with another

pedal unit. Finally, they sterilise the towels by exposing them to ultraviolet light, trimming the end product and affixing strips before packing.[30]

This design of the machine is not aimed at manufacturing the maximum possible napkins per unit time, which would be the means to maximize profit. Instead, it is aimed at simplifying the building of the machines, and an ease of operation (and maintenance) by lay people, including women who may not otherwise have exposure to machines. 'The technology used is simple and non-chemical. In fact, the machine uses purely mechanical processes such as grinding and defibration, pressing and sealing to convert the raw material – high-quality pine wood pulp – into a napkin.'[31] His machines are also less dependent on electricity, as they use human power. The activity is not menial, as it has room for active human engagement with the process and the product. This is especially true because the consumers/users are themselves (or represented by) the producers/manufacturers here.

(4) The central value guiding AM's design is not efficiency geared towards maximizing the output and minimizing the raw material, which is the most important technical and engineering value currently. On the other hand, this is the central value in the mostly multinational napkin industry, where the manufacturing machines are designed to maximize efficiency, which also maximizes profit – efficiency works as a proxy for profit. This design is centralized, and thus not oriented towards sanitary health, livelihood generation, or women empowerment. Commenting that the multinationals only served the educated and the rich, AM says: 'For the last 60 years they talked about comfort. But what about hygiene?' The pursuit of techno-economic efficiency led to a design that only satisfied the profit-making goals of a few, and the comfort of the upper strata of society, while AM's grassroots design demonstrates the possibility of a 'universal good' design space, where the notion of efficiency is wider, covering women's health, livelihood and empowerment, at all levels of society. This wider socio-technical and network approach to efficiency, and the equitable and sustainable design space that such an approach opens, is lost when designs are driven exclusively by purely input–output approaches to efficiency.

(5) AM's technical as well as business model enables many small groups to start their own backyard or cottage-industry. This allows for a more decentralized production and distribution chain, resulting in local access to both livelihood (work) and the product. 'He believes that big business is parasitic, like a mosquito, whereas he prefers the lighter touch, like that of a butterfly. A butterfly can suck honey from the flower without damaging it, he says.'[32] His company sells the machines directly to rural women with the help of bank loans, as well as through NGOs and women's self-help groups. An operator can learn the entire towel-making process in three hours and then employ three others to help with processing and distribution.[33]

This business model does not force a large number of (most likely male) workers to a centralized manufacturing facility, away from their homes or even hometowns, or make them almost non-human parts of the automated conveyor belt and supply chain.

[30] Sandhana, *India's Women Given Low-Cost Route to Sanitary Protection*, 2012.
[31] Jayaashree Industries, *About Jayyashree Industries*, 2017.
[32] Venema, *The Indian Sanitary Pad Revolutionary*, 2014.
[33] Sandhana, *India's Women Given Low-Cost Route to Sanitary Protection*, 2012.

Manufacturing workers are thus not uprooted from their locale in order to access this livelihood, but instead can make this an addition to their diverse basket sources of livelihood, thus making their lives more sustainable. They also have the benefit of working to their schedule, juggling various activities as needed. AM's design thus incurs fewer social costs by 'Solving for Pattern'. Further, a lightweight and voluminous product like the sanitary napkin, when made at a centralized facility, would also incur a high transportation cost. AM's business model allows local production and saves transport cost, at the same time reducing the players involved in the supply chain – the third person to handle the product (from its inception) is the consumer.[34] He thus also reduces the environmental costs of his technology.

3. EP's micro hydro power systems

Alternate hydro power solutions in mountainous regions contribute to sustainability, as they do not damage the ecology, and do not displace people from their homes and villages, as happens very commonly with mega power generation based on big dams. The present case study discusses the process of designing such micro hydro turbine systems by a formally trained engineer, EP. We trace the historical trajectory of his installations (four episodes), and analyze the ways in which his designs contribute to sustainability, and the way his design approach changed from the approaches learned in the engineering classroom.

(a) Modified traditional water mill: In 1975, fresh out of college, EP developed his first power generation solution for a research lab in the high-altitude region of a protected National Park. Due to lack of funds and remoteness of the site from the state power grid, EP modeled a water turbine on the traditional water mills installed on perennial streams in the region. EP's modified design increased the shaft's rotations per minute (rpm) by 10–12 times, from 300 to about 3000. This was coupled to an alternator that charged a DC battery. The success of this first micro hydro power system initiated a journey for EP that was quite different from the corporate and academic careers usually taken by engineers from eminent engineering institutes like his.

> So, after this we jumped on to another thing ... how do we run a small power station in a village?[35] [EP]

While he worked as a government consultant and for NGOs, he continued to build micro hydro power systems for remote villages.

(b) Pelton turbines and Digital Load Controllers: EP had studied that a Pelton turbine can handle variations in flow and is good for high head situations. So he designed technically sophisticated Pelton turbines for such sites from 1978.

> ... so hydro-machinery, hydraulics is a subject. And we have done experiments in the lab. So we are very well conversant with the turbines. We know it. So after that if you look up the literature, you know about the shapes, you can design according to that. The only problem I had was, I was a civil engineer, so I had to get into mechanical ... part .... But, initially I did all the work myself. [EP]

[34] Jayaashree Industries, *About Jayyashree Industries*, 2017.
[35] From semi-structured interviews of EP.

In 2005, EP built a Pelton-based micro hydro power system for two tribal villages in a remote area set in the middle of a reserve forest, through an NGO working there since 1979. The source water flow – a waterfall nearby – would vary throughout the year, but it offered a good head. In order to cope with the seasonal variation in the input flow, EP provided two alternators, generating 10 kW for low flow and 25 kW for high flow. To manage the variation in electric load, EP designed a Digital Load Controller (DLC) and each house was fitted with a variable load controller with manual reset. 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.[36]

(c) Cross-flow turbines and heating coils: When a good flow of water was available throughout the year, EP designed cross-flow turbines that work well at low heads. A cross-flow (Banki or Ossberger) turbine is simpler to design, fabricate, and maintain. '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.'[37]

He also used the simple system of heating coils as dummy loads to address load variation management, ensuring safety at a lower cost, complexity, and maintenance, though at a loss of power.

> 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. [EP]

(d) Electro-mechanical power generation: In 2006–2009, EP's NGO was an implementation partner for a renewable energy ministry project in a remote mountain district. EP designed for two turbines running side by side: one turbine for electricity generation and another turbine for motive power application when no electricity was required. He involved local labor and trained some to be grassroots engineers for the fabrication, construction, and maintenance activities.[38]

Further, EP designed scaled-down machinery for livelihood generation, drudgery reduction, and income earning based on local natural resources, through wool washing, wool carding, spinning, oil milling, flour milling, and rice threshing.

> . . . after doing the (village name) 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. [EP]

3.1. Analysis of EP's designing

EP started with formal engineering training, but his very first case exposed him to various real-world constraints as well as opportunities arising from the socio-economic context. Nevertheless, his focus remained technical, until later projects exposed him to many

[36] Vaghela, "Powering Dignity," 2006.
[37] Wikipedia, "Micro Hydro," 2016.
[38] RERL, "Renewable Energy for Rural Livelihoods in MNRE-UNDP-FRG Project Villages in Rajasthan and Uttarakhand," 2009.

non-technical parameters of the problem situation. This led him to explicitly incorporate these parameters in his task specification, and to design for a network of multiple factors rather than input–output efficiency. His design space widened beyond the mere techno-scientific, and his experiments with the plasticity of socio-technical connection gave rise to an alternate model of designing technology for society.

This historical analysis of some of the key transitions in EP's design process illustrates how EP reformulates the need definition or the problem space in each subsequent design situation, thus effectively 'Solving for Pattern', which is an explicit focus in his current designs.

(1) In the initial projects, EP was primarily focused on the technical aspects of providing electricity, but not involved in the community exercise.

> We thought that village Pradhan, or head of the village, is taking care of all this. Actually it was not getting into our thinking process.. that it is very important to have the community with us. [EP]

Even while working with NGOs that had a mandate of ensuring inclusion, social and gender equity, and sustainability, as well as implementing the project with community participation, the technical was prioritized.

> 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 the community not valuing the system and no fund for future repairs and maintenance.[39]

Also, EP fabricated the Pelton turbine in his city, and the community had no experience of handling issues related to it. The project report documents[40] that although it was planned that the project would be handed over to the community for maintenance, this created several glitches. In later projects, the NGO emphasized training local people to fabricate the turbines locally. Further, EP had developed and used a DLC. Digital technology often needs a trained and equipped person for its maintenance, troubleshooting, or repairs, and this may be expensive or not readily available locally.

With such experiences, EP reconsidered his choice of components and modified his power system design for subsequent projects, from the point of view of ease of fabrication, installation, and maintenance in the context of the users and conditions in the remote villages.

> . . . 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 . . . [EP]

EP's recent projects are now conceived on the model of the electro-mechanical livelihood project. 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 . . . 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' [EP].

[39] Vaghela, "Powering Dignity," 2006.
[40] Vaghela, "Powering Dignity," 2006.

(2) 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. 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. One possible perspective on this case is that EP is 'customizing' a core engineering solution, which optimizes input–output performance. However, this view is based on treating input–output optimality 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 input–output efficiency model. According to Gary Downey,[41] 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 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.'

(3) Although the building of large dams has been justified for efficient generation of mega power through centralized water source, EP is now a strong proponent of the micro hydro turbine as an ideal renewable source of energy at least for the mountain areas. As his design demonstrates, it is the most economically, socially, as well as environmentally sustainable solution, and there is no need to design a centralized, large-scale (mega power) system in order to achieve economic feasibility. A micro hydro system incurs far fewer environmental costs than a mega power dam. A micro hydro system induces minimum disturbance to the natural ecosystem of a water source, as required water is diverted and merged back into the source flow, without blocking the mainstream with dam walls. The natural niche habitats and life cycles in the water stream are thus conserved. Social costs of displacing villages that would be submerged in the backwaters in case of mega dams are also not incurred.

Further, the economic viability of micro hydro systems can be ensured using simplicity of design and by including income-generation components. Maintenance is better managed through local interest and training.

> 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. [EP]

(4) Similar to AM's design, the production and distribution of power in EP's design remain local and decentralized. This not only avoids major distribution losses incurred by long-distance grid-based transmission, but also empowers people to locally control and maintain the system. For example, they have the option to divert water to generate mechanical drive when electricity is not required, or to prioritize water for irrigation if necessary. Furthermore, even the technical specifications of the system can be designed to cater to specific

[41] Downey, "PDS: Engineering as Problem Definition and Solution," 2015.

needs of the locale, the quality and quantity of power to be generated being decided based on its intended specific applications. EP's design approach allows designing systems based on diverse applications such as grinding mills, lighting, car-washing compressor, wool-processing machine, or restaurant ovens.

(5) EP's key design changes are interconnected in his person. His explicit design preferences, in the reformulated task specifications, are a coagulation of his years of experience addressing complex grassroots problems. Students, unless trained, may take many years to understand the need and method to do this, if at all.[42]

4. Danish wind technology

During the energy crisis of the 1970s, many countries, such as Denmark, France, Germany, UK, USA, and the Netherlands, struggled to develop modern wind technology as a source of power. Of these, the Danish wind turbine systems proved to be the most successful, despite the high-tech competence and high capital investments of other countries.[43] This success came from a socio-technical approach to engineering, and this case of development of wind power in Denmark has been included in the philosophy of engineering course taught to undergraduate engineering students at Aarhus University, to help teach them social perspectives of engineering.[44]

In the early twentieth century, rural Denmark used electricity generated from wind power on a small scale. Danish scientist and wind power pioneer Poul la Cour's 'Klapsejler' (clap-sailor), a 'simple, robust, and reliable windmill, producing direct-current (DC) power', was a major generator of this wind power, especially during the fossil fuel shortage during World War II.[45] When Denmark turned to AC power after World War II, and started exploiting oil from the North Sea (in the 1960s), many windmills were phased out. Nevertheless, innovations in wind power designs continued in Denmark, as also in France, Germany, UK, USA, and the Netherlands.

In the late 1940s, Johannes Juul, a Danish electrician who had trained with Poul la Cour, started developing wind turbines to produce AC power, and to supply it to the Danish electricity grid. Based on the test runs of his initial two-bladed turbines, he decided to build three-bladed turbines. Similarly, after experimentation with small prototypes and test run observations, he modified the rotor position from downwind to upwind, and the yaw control from passive to active. The 200 kW turbine he built in Gedser in 1957 ran successfully for 10 years.

Based on this turbine, and Juul's designs, carpenter Christian Riisager and blacksmith Karl-Erik Jørgensen started building simple wind turbines.

> Riisager assembled his first wind turbines from inexpensive off-the-shelf parts, such as standard asynchronous generators and truck gears, axles, and brakes. In spite of his limited theoretical

[42] Date and Chandrasekharan, "The Socio-technical Connection Is Plastic, But Only When Design Starts from Need Formulation," 2016.

[43] Kamp, "Socio-technical Analysis of the Introduction of Wind Power in the Netherlands and Denmark," 2007; Heymann, "Signs of Hubris," 1998; Karnoe, "Technological Innovation and Industrial Organization in the Danish Wind Industry," 1989; Stoddard, "The California Experience," 1986.

[44] Heymann, "Engineering as a Socio-technical Process," 2015.

[45] Heymann, "Signs of Hubris," 1998, p. 649.

> background and experience, by 1976 Riisager had produced a surprisingly reliable 22-kilowatt turbine.[46]

'By January 1978 he had sold six copies; within the next two years he sold fifty more.'[47] As Matthias Heymann[48] comments about their craft-like method, 'Practical experience turned out to be a key advantage. It gave rise to a rich base of personal "tacit" knowledge, a feeling for forces and loads and for the performance and limitations of technical components.'

Many small manufacturers followed Riisager and started supplying small wind turbine generators to the Danish people. Initially, those who wanted independent electricity sources, even at a higher price, purchased the wind turbines. Later the government offered credits and market subsidy, and the demand increased substantially. The Danish government established a test station to test and provide licenses for the turbines. Since government subsidy could be availed only by licensed turbines, commercial manufacturers had to work with the test station engineers to standardize their turbines. With a rise in demand that could not be met by the small manufacturers, other companies such as agricultural machine manufacturers purchased their designs and entered the business of commercial wind turbine production.

When wind-based renewable energy attracted attention during the fuel crisis of the 1970s, the governments of countries like USA, Germany, and Denmark invested large amounts of capital and trained manpower into organized research and development of large wind turbines. The most successful turbines though were not the ones built by the government R & D programs, but by the Danish commercial manufacturers.

> The American failure looks even worse when one considers that between 1975 and 1988 the United States government spent twenty times (and Germany five times) as much for wind power research and development as did Denmark, yet Danish manufacturers made better turbines.[49]

Danish commercial turbines were developed independently of the government R & D programs.[50] In the 1980s, major wind turbine installations were put up in California. Of these, 45% were supplied by about six commercial manufacturers from Denmark.

4.1. Analysis of Danish wind technology designing

Contrary to the technology design driven by engineering sciences and mathematics, Danish wind technology (DWT) designs by technicians and craftsmen proved to be more reliable and cost-effective. This superiority of Danish designs showcases yet another model of alternate socio-technical connection. Scholars have discussed many factors leading to this, not limited to the technical design, or the process alone, but to significant extent factors such as the socio-political context and interaction opportunities.

(1) Designing wind turbines proved a challenging technical task due to static and dynamic loads, wear and tear, and the need for automaticity and constant rotor speed for AC. Design efforts are driven by engineering sciences and mathematics aimed for high

[46] Karnoe 1978, cited in Heymann, "Signs of Hubris," 1998.
[47] Heymann, "Signs of Hubris," 1998, p. 661.
[48] Heymann, "Engineering as a Socio-technical Process," 2015, p. 480.
[49] Heymann, "Signs of Hubris," 1998, p. 642.
[50] Heymann, "Signs of Hubris," 1998, p. 668.

efficiency, and their design decisions were thus narrowly focused on optimization of input–output parameters. Forrest Stoddard[51] identified the key technical differences in the way the American, German, and Danish turbine designers responded to these challenges, particularly as seen in the turbines installed in California in the 1980s, and attributed Danish robustness to their technical design decisions. While the Danish turbines featured three blades, upwind rotors, active yaw control, stall control, and medium or heavyweight, the American large-scale ones, oriented towards increasing the aerodynamic efficiency, preferred two blades, downwind rotors, passive yaw control, pitch or semi-pitch control, and were extremely lightweight.[52] 'Although American and German turbines ran more efficiently, they proved less reliable and cost-effective than Danish turbines.'[53] The foundations for these two different trajectories were laid early on, with Putnam building a 1250 kW grid-feeding AC turbine in the early 1940s, in the USA, while Juul starting with a small 15 kW grid-feeding AC one in the late 1940s in Denmark. According to Peter Karnoe,[54] the Danish process was bottom-up, following a step-by-step process based on incremental learnings through practical experience. In Germany, on the other hand, Ulrich Hutter developed basic design principles based on the theoretical aerodynamics of wind turbines, promoting 'a small number of blades, clean aerodynamic profiles, high rotor velocity, and extremely light construction to achieve the major design priorities of high efficiency and low weight'.[55] In the USA, NASA and large aircraft companies were engaged in developing turbine technology projects undertaken for the government. They preferred Hutter's principles over Juul's designs. But their designs failed technically as well as economically. 'A bigger-is-better ideology and a strong belief in technical efficiency characterized most government-supported R&D efforts, especially in Germany and the United States.'[56] Heymann calls this engineering approach as science-based, while that of the small Danish manufacturers as practice-oriented.[57] He concludes that 'Reliable and successful wind turbine designs have mostly been developed by nonacademic engineers, technicians, and artisans in Denmark, while the designs proposed by academic engineers in the1970s and 1980s mostly failed.'[58] He remarks, 'Wind technology development in the academic and large-corporate world illustrated an excess of ambition and confidence that could more precisely be named technological hubris.'[59] Different knowledge bases also create different orientations, values, mentalities, and ideologies. Craftsmen were conservative, while theoretically trained engineers exhibited ambition for innovation and confidence, but under-estimated the challenge. Linda Kamp[60] points out that the design process of small-scale entrepreneurs is guided by 'learning by doing, using, and interacting', while that of the R&D institutions is by 'learning by searching'.

[51] Stoddard, "The California Experience," 1986, cited in Heymann, "Signs of Hubris," 1998.
[52] Stoddard, "The California Experience," 1986, cited in Heymann, "Signs of Hubris," 1998, p. 643.
[53] Heymann, "Signs of Hubris," 1998, p. 648.
[54] Karnøe, "Technological Innovation and Industrial Organization in the Danish Wind Industry," 1990.
[55] Hutter, 1942, cited in Heymann, 1998, p. 653.
[56] Heymann, "Signs of Hubris," 1998, p. 667.
[57] Heymann, "Engineering as a Socio-technical Process," 2015, p. 477.
[58] Heymann, "Signs of Hubris," 1998, p. 666.
[59] Heymann, "Signs of Hubris," 1998, p. 668.
[60] Kamp, "Socio-technical Analysis of the Introduction of Wind Power in the Netherlands and Denmark," 2008.

(2) In Denmark the design process also occurred in the context of many socio-economic-political factors that came together in support of wind technology development, while this was missing or in opposition in the other countries. Early user involvement was supported through interest in renewable energy, as well as a market subsidy, from the government. User feedback on early installations, and their long-term performance, thus played a role in modifying the designs to better suit the market. Forums such as 'wind meetings' and the journal *Naturlig Energi* resulted in designers, manufacturers, users, and government bodies keeping up-to-date on various developments as well as issues in DWT design. This allowed for an open exchange and cross-pollination of ideas and experiences, not only in terms of product design, but simultaneously also on the other fronts such as manufacturing, distribution, governance, policy, and market development for DWT. This indirectly led to a much wider design space, where the need definition or problem framing encompassed multiple technical as well as non-technical aspects of the technology. Government played an indirect but significant role in bringing about improvements through building a test station, and offering technology subsidies to the designers. This ecosystem of a collaborative design was further nourished by socio-political support through renewable energy movement within Denmark. Thus, in DWT design, the society–technology connection was far expanded to include various stakeholders and institutions, where all converged to provide the environment necessary for the success of DWT.

(3) The socio-technical process of DWT design was thus not centralized and concentrated in one place, nor was it a captive to a singular design direction. The decentralized nature of its design, manufacturing, and distribution further contributed to a wider design space and the better sustainability of the solution.

5. Collective findings from the three cases

The three cases demonstrate a deep and long-term engagement of the designers with not only the problem but also with the societal and socio-political-environmental context which constitutes the problem. The design effort is not focused on implementing a particular theory-driven efficient technological solution, but on addressing the problem in all its complexity. Further, these case studies bring out this complexity of real-world messy problems, where implementing even simple or 'known' technologies becomes a challenge, and it takes persistent effort over extended periods of time (even with formal training), to arrive at novel and successful designs that really make a difference to society. Each of these designers demonstrates that the real job of designing technology does not start with a given 'frozen' task specification, nor does it end with calculations to arrive at technical specifications. It needs to take into account the socio-technical connection and work with the plasticity that it affords.

Collectively these three cases illustrate and help emphasize the following main findings (see also Figure 1).

(a) The design space is widened by changing the socio-technical connection, and this plastic understanding of the socio-technical connection enables innovation.

Once the socio-technical connection is taken into account, there can be many possible designs and no single efficient or optimal solution. In this sense, the connection between product/technology and society is actually fluid or plastic and supports wider innovations.

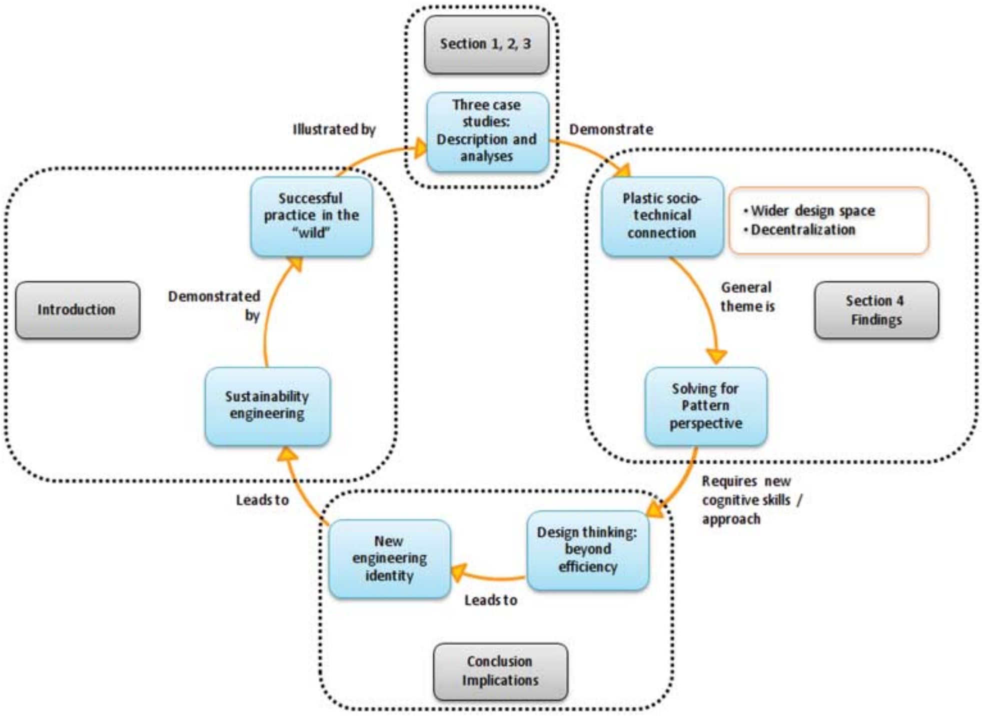

Figure 1. Argument map.

In practice terms, this plasticity is available only if the designer begins at the need/problem definition stage, which allows for a much wider design space. The default industrial socio-technical connection is just one possible design.

AM's case demonstrates the extent to which requirements need to be understood, and the length an innovator goes to arrive at such an understanding, in order to design a satisfactory solution. His design then has the power to affect the society, at levels wider than the one it is embedded in, in innovative ways. To develop a design approach that allows such fluidity in practice, in the words of Louis Bucciarelli,[61]

> Nothing is sacred, not even performance specifications, for those, too, are negotiated, changed, or even thrown out altogether, while those that matter are embellished and made rigid with time as design proceeds. . . . Specifications become artifacts of process, reconstrued in the engaging of different perspectives of different object worlds.

EP's case illustrates how the interaction with socio-ecological needs influences and broadens his task specifications, and in turn changes the embodiment of the technological solution, in order to meet the society's needs.[62] Once the socio-technical connection is understood as a plastic relation, and many different designs are developed to connect the technology differently with eco-social requirements and groups of people, the design possibilities are very wide and interesting, where standard design categories (such as product, manufacturing, embodiment, and concept) can be recombined in novel ways.

[61] Bucciarelli, *Designing Engineers*, 1994, p. 187.
[62] Date and Chandrasekharan, "The Socio-technical Connection Is Plastic, But Only When Design Starts from Need Formulation," 2016.

Engineering design practice, and engineering education, misses out on this wider design and innovation space when the society–technology connection is framed by default as the industrial one, which restricts the design space – the direction of exploration for solutions – to 'within' the detailed design phase of the design (problem-solving) process. In such a practice, the designer works with a pre-defined and 'frozen' task specification that embeds the currently dominant centralization assumptions, including centralized manufacturing processes. As illustrated by the AM case, this approach incurs many social and environmental costs that are conveniently externalized, leading to socially and environmentally unsustainable technological solutions. Starting from the default model, there could be a continuum of socio-technical designs, going all the way to full decentralization, including full sharing of surpluses (as in the AM case), or partial centralization and an equitable sharing of surpluses (as in the cooperative case).

AM designed a technology such that a for-profit business model could be based on a small, decentralized manufacturing set up, situated close to the workers. The model is amenable to their way of life, and also located in the midst of the consumers of the product, which made the distribution chain shorter. This decentralization allowed each individual setup to create their own brand, and cater to a catchment of users in their vicinity as well as within their manufacturing capacity, thus achieving a deep penetration of market without any media-based advertising. The technology became sustainable because its design also supported a more equitable distribution of wealth through this decentralized model. Similarly, EP's decentralized power generation allowed for better socio-environmental sustainability than any centralized power plant based on big dams. The DWT design process itself was highly decentralized compared to American or German institutionalized R&D, and contributed largely to its socio-technical problem framing and solving. The DWT system, with its lower power output, was also more amenable to decentralized, individual use within Denmark, thus leading to Denmark's success as a country utilizing largely renewable and sustainable source of power.

It is interesting to note here that while the classical, efficiency-driven production processes focus on centralization, new digital and software technologies from Silicon Valley (such as Kiva and Kickstarter) demonstrate more social engagement and a decentralized approach embedded in their designs. More generally, the social is now a key component of software design. This trend suggests that expanding the design space, and decentralization as one way to do it, may be a requirement even within the standard model of engineering design, where sustainability is not a central design concern.

(b) Solving real-world problems successfully to meet the unmet needs of many, in a sustainable fashion, requires solving for larger patterns, not for singular 'most-efficient' solutions.

Technical performance and economic optimization have been held up as the prime goals of the design. But many scholars have pointed out that technical and economic efficiency is not the only or the best norm to aim for, if sustainability problems are to be addressed. Nor are there any singular most-efficient designs. Throwing out the hard autonomy of technology argument, Bucciarelli[63] posits that 'Only after the artifact is fixed does it appear otherwise, as rational . . . In process there are many objects, many potential artifacts, many object worlds. . . . Science push and market pull, optimization and satisficing

[63] Bucciarelli, *Designing Engineers*, 1994, p. 196.

are not determinate.' An elaboration of this can be seen in Heymann's comment, 'Technology development takes place in and makes part of a larger context of power relations, market structures and policies as well as beliefs, values and ideologies.'[64] In fact, using historical examples of Moses' low bridges and McCormick's molding machines, Langdon Winner even points out how efficiency itself has been sacrificed for (vested rather than fair) political and social interests.

> If we suppose that new technologies are introduced to achieve increased efficiency, the history of technology shows that we will sometimes be disappointed. Technological change expresses a panoply of human motives, not the least of which is the desire of some to have dominion over others even though it may require an occasional sacrifice of cost savings and some violation of the normal standard of trying to get more from less.[65]

A perspective rooted in the centralized revenue model would consider EP as merely '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 our analysis of these cases is that, in mainstream design, 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. For example, in the context of various energy studies during the energy crisis of the 1970s, Langdon Winner[66] observes, 'Regardless of how a particular energy solution would affect the distribution of wealth and social power, the case for or against it had to be stated as a practical necessity deriving from demonstrable conditions of technical or economic efficiency.'

Such externalization of socio-ecological costs fails to serve the society in the long run, even though technical efficiency is geared towards the performance goal of meeting society's needs at a minimum economic cost. While sustainability is not opposed to profit, and while it does not imply that all profit-making engineering design, be it capitalist, cooperative, or socialist, is necessarily unsustainable, the exclusive focus on profit-making and techno-economic efficiency, ignoring the interconnected nature of technology and socio-ecological aspects, invariably leads to unsustainable solutions.

Also, in some profit-making engineering design practice, socio-ecological considerations may remain add-on features that are subject to trade-offs (such as the use of plastic versus aluminum in laptop covers). Such trade-offs essentialize an estimation of the value of the socio-ecological consideration, a quantification that can be compared with other considerations. Although such trade-offs are a step towards sustainability, the practice in such cases is limited to only those socio-ecological considerations that can be quantified and traded off. These continue to operate in the paradigm of the technical, and fall short of breaking out of it. As Bucciarelli[67] suggests, based on the analysis of ethnographic data of three design teams, 'Designing is not simply a matter of trade-offs, of instrumental, rational weighing of interests against each other, a process of measuring alternatives and options against some given performance conditions.' Wendell Berry's idea of 'Solving for Pattern',

[64] Heymann, "Engineering as a Socio-technical Process," 2015, p. 487.
[65] Winner, *The Whale and the Reactor*, 2010, p. 24.
[66] Winner, *The Whale and the Reactor*, 2010, p. 53.
[67] Bucciarelli, *Designing Engineers*, 1994, p. 187.

described in the introduction and illustrated by the three cases, thus better captures the broader perspective that allows the interconnectedness of things in the world to guide the design decisions, instead of quantified trade-offs. This leads to a more holistic and socio-technical approach to efficiency and sustainability.

Such qualitative aspects of the socio-technical approach to sustainability may appear to be vague and subjective, when viewed from a rational, instrumental approach. It needs to be noted though, that technology design is a process of negotiation between various stakeholders. As Vermaas, Kroes, van de Poel, Franssen, and Houkes[68] argue, 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'.

A socio-technical efficiency approach makes it possible for an engineering designer to be sensitive to those voices that are weaker at the articulation and negotiation of their real needs. This also includes the voices of other species. 'Solving for Pattern' essentially brings in the understanding that meeting only human needs at the cost of the well-being of other species, as well as the interdependence of species, cannot lead to sustainable solutions. The unarticulated, vague, and subjective get defined better through the negotiation process, rather than a designer alone trading off parameters based on her/his 'objective' understanding of the situation.

Design approaches driven just by input–output efficiency, and its associated value system, would direct the design imagination away from approaches such as AM's, where the design focus is on building a semi-automatic machine, mostly run on human power. Driven by optimization motives, AM would either set up a large, centralized, manufacturing factory, or sell his design to a company that would do this. There would be no women-empowering social system built around the technology. EP would not design for livelihood-supporting decentralized technologies based on micro hydro turbines, instead of mega hydro powers based on unsustainable dams. In the face of competition from advanced R&D labs in the USA and Germany, Denmark would not set up an example for the world, on the way to design alternate energy models.

In summary, these three cases demonstrate what Langdon Winner pointed out as the idea-level contribution of the appropriate technologists a few decades earlier.

> They [appropriate technologists] helped broaden the meaning of such categories as 'efficiency,' 'rationality,' 'productivity,' 'cost,' and 'benefit' and added fresh (if not altogether novel) criteria of judgment-'human scale,' 'the interconnectedness of things,' 'second law efficiencies,' 'sustainability,' and the like – to the range of considerations that engineers, technicians, agriculturalists, planners, and consumers ought to take seriously in making choices.[69]

6. Implications

> . . . engineering is more than developing technical artifacts. It is a way of 'mixing with the world' in a much broader sense than reflected in many engineering curricula.[70]

[68] Vermaas et al., "A Philosophy of Technology," 2011, p. 95.
[69] Winner, *The Whale and the Reactor*, 2010, p. 82.
[70] Heymann, "Engineering as a Socio-technical Process," 2015, p. 477.

These designs emerge from the plasticity of the socio-technical connection, and this design space 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, without exposure to need identification and problem definition/framing. These cases indicate that students need to be trained for such problem framing, conceptual and embodiment design phases, and not merely the detailed design phase employing sciences and mathematics, in order to design for eco-socio-technical efficiency.

Donald Schon 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.[71]

He advises that 'we should not start by asking how to make better use of research-based knowledge but by asking what we can learn from a careful examination of artistry, that is, the competence by which practitioners actually handle indeterminate zones of practice . . . '[72] He discusses uncertainty, uniqueness, and value conflict as the indeterminate zones of practice, and comments that these have come to be seen 'as central to professional practice', rather than the well-formed instrumental problems taught in engineering curricula.

All the three cases we present demonstrate this, and Heymann underlines particularly in the DWT case that

> . . . the knowledge generated through practical experience is of crucial importance to technical design. . . . It is a type of knowledge that cannot be replaced by or transformed into theoretical knowledge. . . . As tacit knowledge cannot be taught in classes, it tends to be undervalued or even ignored in engineering curricula. Reflecting on cases like wind turbine development helps to make it more visible.[73]

The development of the Danish wind turbine elaborates how hands-on artisans conceptualize and prioritize parameters of wind power generation vis-a-vis theoreticians, and how a bottom-up designing process brought together many stakeholders to enable a robust socio-technical design rather than an ambitious technical failure. Kamp comments,

> As Rosenberg writes (Rosenberg, 1982) learning-by-using is especially important in connection with products that consist of complex, interdependent components. When these products are used, especially when they are subject to prolonged stress, the outcome of the interaction of the components cannot be precisely predicted by scientific knowledge or techniques. Therefore, in the case of wind power it is especially important to gain a lot of experience with the technology while it is in use, either as a prototype or as a commercial product. The Danish way of trial-and-error, slow upscaling and early market development proved to be more suited to this specific technology than the Dutch way of high-tech fast upscaling and science-driven technology development. However, for another, more science-driven innovation like nanotechnology, this approach could prove to be more fruitful.[74]

The bottom-up design process of DWT is an alternative path that underlines the necessary interaction of socio-ecological context with techno-scientific knowledge in the design

71 Schon, "Educating the Reflective Practitioner," 1987.
72 Schon, "Educating the Reflective Practitioner," 1987.
73 Heymann, "Engineering as a Socio-technical Process," 2015, p. 481.
74 Kamp, "Socio-technical Analysis of the Introduction of Wind Power in the Netherlands and Denmark," 2008, p. 290.

process. In the words of Bucciarelli, 'The scenario about science determining form, as ordinarily understood, misses the complexities of alternative forms and paths to a design.'[75] This approach does not undermine the role and value of formal knowledge in design, it just puts it in a wider perspective. This wide perspective, when missing, leads to top-down, theory-driven technology design that recklessly optimizes input–output efficiency. This approach has damaged the planet's ecosystem over the last several decades, bringing into sharp focus a need to design for sustainability. If engineering sciences, in the process of meeting society's short-term needs, or while creating such needs, externalize these considerations, then they fail to address the society's long-term sustainability needs.

For sustainability to be more than an afterthought, or an add-on to be practiced merely to meet legal requirements, the scope of a designer's activity needs to be understood as much wider than, say, for example, the current definition of Engineering design, by ABET's[76] as

> the process of devising a system, component, or process to meet desired needs. It is a decision-making process (often iterative), in which the basic sciences, mathematics, and the engineering sciences are applied to convert resources optimally to meet these stated needs.

Gary Downey[77] poses the crucial question of whether the problem of reforming engineering education for the future is at core the problem of reimagining the very identity of engineers. Findings from the cases discussed here clearly highlight the need for an identity, approach, and thinking that goes beyond the current engineering identity based on formal knowledge of sciences and mathematics.

Further, the cases discussed here outline a spectrum of role models that bring forth a diversity of possible identities in the practice of engineering design for sustainability. While the DWT artisans have been innovators and private entrepreneurs, AM is a social entrepreneur and EP is a development consultant. These cases demonstrate that such a new engineering design identity can be formed around design thinking based on the 'Solving for Pattern' perspective.

Integrating such case studies in the engineering curricula may be one way to expose future engineers to such identities and role models. The cases would also provide ways in which designers can situate themselves in real-world problem contexts, or embed engineering design learning in authentic contexts.

> Case studies are examples of ill-structured problems that may be used to help students understand more complex and ill-structured problems. That is, students can analogically compare case studies with complex and ill-structured problems to solve in order to construct problem schemas and consider alternative perspectives and solutions.[78]

While courses on Ethics or sustainability may broaden the knowledge base, it may still be only a descriptive understanding. Instead, the case of say EP could be integrated with the module on Hydraulic Machines and Design of Turbines. Along with the detailed design problems at the end of the module, the case could be used to discuss the complexity of actually implementing such a design. Akin to Bucciarelli's idea[79] of bridging the context of

[75] Bucciarelli, *Designing Engineers*, 1994, p. 185.
[76] ABET, "Criteria for Accrediting Engineering Programs," 2011.
[77] Downey, "PDS: Engineering as Problem Definition and Solution," 2015.
[78] Jonassen, "Engineers as Problem Solvers," 2014, p. 114.
[79] Bucciarelli, "Designing and Learning," 2003.

design (practice) with the context of learning, such case studies can add the component of engagement, and bring in knowledge, skills, values, and identity in an integrated fashion. Lastly, the case studies, by highlighting these aspects, could help contain the overemphasis on formal knowledge, and ground the design efforts. Exposure to case studies of non-formally trained innovators may also enable better dialogue between practitioners and lay people. This may pave the way for effective participatory designs that could be collaborations between trained designers and lay users.

Even the identity of engineering sciences – which seeks to optimize scientific results and understanding to develop technologies for which needs do not yet exist – may benefit from such a widening of the design space. A good example of this is the recent development of the 'paperfuge'[80] – a low-cost hand-operated centrifugal machine for testing blood, to address the problem of limited electricity access in medical labs in Africa. The design used microfluidic technology, and also illustrated that the rpm achievable by hand are much more than previously thought. The design thus developed a real-world application based on a cutting-edge technology, and also contributed back to the science of rotation, all starting from a social need.

Training for performance optimality alone is thus highly limited from a design perspective, as it is the same as training to design for maximal profit. Current engineering education has accepted the narrow optimality-profit combo as the only design value and norm. This approach to design is clearly not what engineering education ought to be taking, particularly now that sustainability is a key engineering norm. This perspective blinds engineers to wider design possibilities, and also works as an implicit device for capturing/directing the engineering workforce towards solutions and structures that are unsustainable. The contrasting case of DWT is already a part of Aarhus University (philosophy of engineering) curricula for undergraduate engineering students.[81] We suggest that case studies such as DWT, AM, and EP, when integrated with the respective modules in engineering curricula, could support the development of an alternate engineering identity, and thereby shift engineering design education and practice more towards sustainability.

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