Solving for Pattern
An operational-level model to redesign engineering education for sustainability

Synopsis

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Abstract

The practice of building novel structures and artifacts is central to human adaptation. Engineering is the modern version of this adaptive practice. However, this adaptive trait is now in runaway mode, as building activity has damaged the planet significantly. Changes in our current approach to engineering and design are thus critically needed to address the changing face of global climate, and the sustenance of our biosphere, while also addressing the current and future requirements of society.

One of the areas to initiate this change is engineering education (EE). However, an integrated understanding of how building is related to society and nature is lacking in EE, and sustainability values and ethics remain on the periphery of engineering curricula. An analysis of current reforms to EE, based on a wider literature on technology and society, suggests that the reforms are limited, and a successful pedagogy for sustainability engineering cannot be built around canonical models of EE. Further, the mainstream engineering practice does not offer any alternate models of sustainability engineering for EE.

A promising approach to develop an operational-level model of sustainability engineering is the systematic study of successful cases that demonstrate sustainability. Following this reasoning, I undertook a study of innovators working at the grassroots, who generate sustainable technology designs 'in the wild'. The objective of the study was to understand, and make explicit, the problem-solving practices, knowledge, skills, and values involved in such design. To do this, I first developed an empirically driven characterization of non-formal grassroots innovation, as well as formal (non-mainstream) sustainable technology design practice, in the Indian context. The findings from this study were then abstracted, to develop two core design principles (Plasticity of the Socio-Technical Connection, Technology to sustain local livelihoods). These were then brought together to develop a

wider design perspective, termed Solving for Pattern, inspired by Wendell Berry's discussion on this topic. The intervention directions based on these principles are applicable more widely to engineering education.

However, given the emphasis on formal structures (engineering sciences and mathematics) in the current engineering curricula, it is unclear how engineering students could be trained to make these design principles a part of their design thinking and approach. To understand this, an analysis of the cognitive processes involved in engineering design was developed, particularly to examine the role played by formal structures in the design process. This analysis showed that imagination (mental simulation of structure and dynamics) is the core cognitive process in engineering design, and formal structures play only a supporting role. Imagination as the core cognitive process of design supports the inclusion of the design principles identified by the first analysis.

Extending the findings from the above studies and analyses, I develop two specific policy recommendations to redesign engineering education for sustainability. Bringing these policy recommendations together, I propose an implementation-level recommendation. I conclude with a discussion of the wider implications of these findings, particularly for research, practice, pedagogy, and policy.

A characterization project

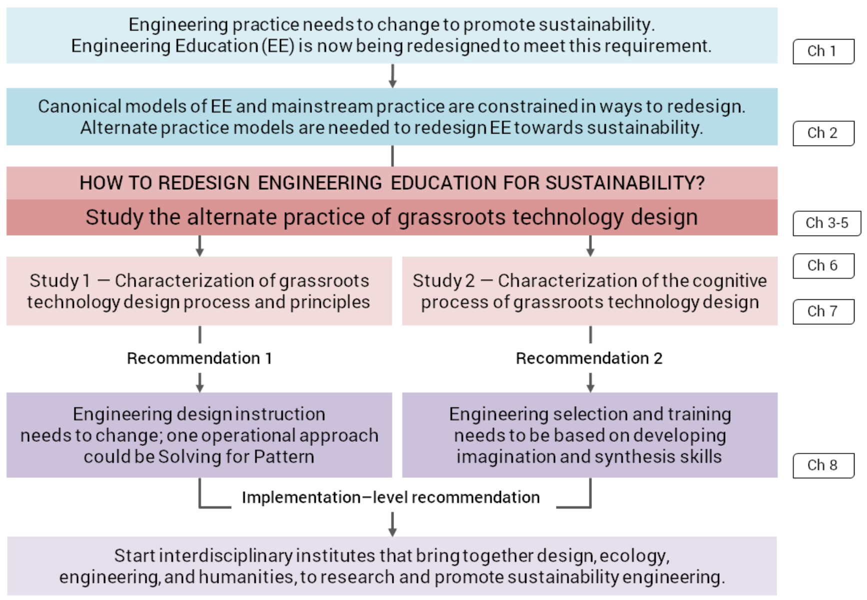

Fig. 1. The research problem, work done, and recommendations.

A graphical summary

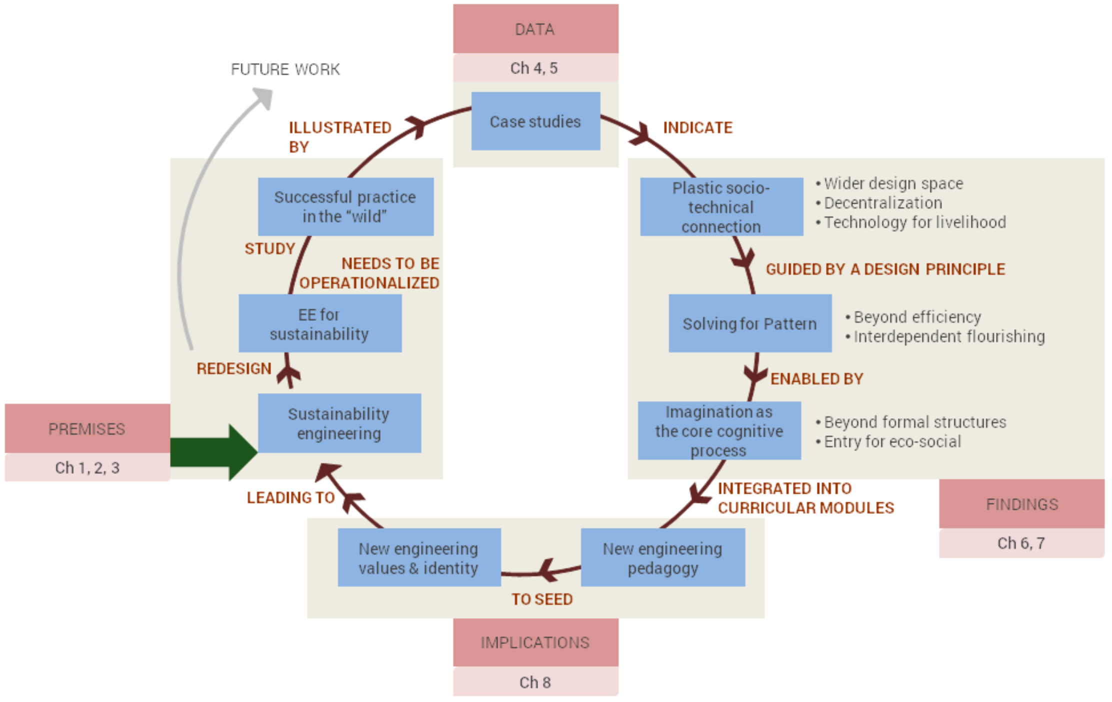

Fig. 2. A graphical summary of the thesis process and argument.

Analytical index of chapters

The analytical index captures the argument of this thesis, and its respective chapter structure in brief. It may thus be understood as an executive summary of the thesis.

Premise and motivation (Ch 1)

The need for a new pedagogy for sustainability engineering

Building is a key adaptive capability of the human species, and engineering is the modern version of this adaptive practice. However, our building activity is now damaging the planet. Engineering practice thus needs to change, to design and build systems that enable a sustainable way of life. One way to do this is through engineering education. Sustainability requires training for a new kind of engineering, but it is not clear how traditional engineering education – in India and across the globe – could be redesigned for this. A possible approach is to study the process of sustainable technology design practice, ‘in the wild’.

Review of literature (Ch 2)

Limitations of the canonical approach to sustainability engineering

The engineering education research (EER) literature identifies some key challenges to training students for sustainability. On the one hand is the overall challenge of broadening the knowledge/skill-base, by fitting more (Sustainability content) into an overcrowded curriculum, and integrating this with the core disciplinary knowledge. Furthermore, the multi-disciplinary knowledge needs to be integrated for sustainability, while ethics, humanities, and social sciences need to be more central to EE. On the other hand, the standard instructor-led learning model is pedagogically not sufficient for developing students as sustainability engineering professionals.

The broader literature (across engineering education, sociology, philosophy and politics of technology, as well as design studies) further points out that EE trains for textbook problems rather than real-world workplace problems, where the problem framing is limited to the techno-commercial, while largely excluding the socio-technical nature of the engineering practice. The contemporary EE is based on a canonical approach to technology and engineering, which considers engineering to be value-neutral and technology-driven, while implicitly prioritizing values of instrumentality and efficiency. Moreover, design is a situated activity rather than mere technical problem-solving. The emphasis in EE on engineering sciences and mathematics as core technological knowledge, and a purely techno-economic focus in the design process, perpetuates a societal disengagement among students, and students' engineering identities develop based on techno-scientific rationality / instrumental thinking alone.

EE reforms to address these issues are segmented and isolated at the level of both curricula and pedagogies, and thus cannot achieve success in integrally addressing the messy complexity of sustainability problems, where the competencies required are still unclear. The current EE approach is thus inadequate to develop an engineering practice for sustainability.

Research approach (Ch 3)

Studying practice ‘in the wild’ - an approach to redesigning EE pedagogy for sustainability engineering

Since mainstream practice does not offer any alternate models to the structure identified above, a satisfactory, and evidence-based, way to redesign EE pedagogy for sustainability engineering needs exploring successful cases of sustainability engineering design in the wild. Such cases are hitherto unexplored from the sustainability engineering and EE perspectives, and research is required to characterize these cases well to contribute to these perspectives.

The thesis project sought to address the above research gap, by exploring successful cases of sustainable technology design practice in the wild. In the Indian context, grassroots innovation[1] is one such practice. The project's objective was to characterize such grassroots technology design well, extract their underlying design principles and cognitive processes, both non-formal and formal, and then use these to develop a new pedagogic approach to support engineering for sustainability. In other domains, similar studies of practice, examining both traditional (medicine, agriculture) and modern (bio-medical engineering)[2] practices, have provided evidence-based ways to design education systems. Following these approaches, a new engineering pedagogy for sustainability could be developed based on studies of sustainable grassroots technology designs, which have not been explored from this perspective.

Research design (Ch 4) and case studies (Ch 5)

Multiple case study – qualitative cross analysis

Grassroots innovation is a unique practice, spread across a wide range of problems and contexts. Given this variety, the case study method was identified as the appropriate method to study this practice. Cases were purposively selected, based on the contribution they could make to engineering education. The case of Micro Hydro Power (MHP) generation systems was chosen as a focus area, as the technology is part of mainstream engineering, and it is sufficiently complex in terms of design process and thinking. Further cases were then selected to provide more generality to the study of this core practice, through comparison and validation. (See Fig. 4).

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[1] Grassroots innovators are individuals, 'not formally trained' in science and engineering, who have been recognized (through National Innovation foundation) for designing technology to address their needs unmet by the formal engineering industry.

[2] Nersessian, *Creating scientific concepts*, 2008; Nersessian et al., “Research laboratories as evolving distributed cognitive systems,” 2003; Nersessian & Newstetter, “Interdisciplinarity in engineering research and learning,” 2014.

The empirical data for the core cases included primary sources (interviews, observation, artifacts, simulation data), as well as secondary sources (photos, videos, and reports, including brochures and news articles). To probe design thinking across both formally and non-formally trained designers in a controlled fashion, a computational simulation of MHP systems, with visual and numeric modes, was developed. Data on the designers' interactions with this simulation provided a different perspective on their design processes.

The data from all these sources were integrated, and qualitatively analyzed using cognitive historical analysis[3] and thematic analysis,[4] to develop a comprehensive understanding of the design practices and their underlying cognitive processes. Distributed cognition[5] was the primary theoretical framework used for studying the cognitive process of design.

Findings 1 - Design practice (Ch 6)

The socio-technical connection is plastic; sustainable technology aims at empowering people and sustaining their local livelihoods

A thematic analysis of the core cases – non-formal and formal practice while designing MHP systems – provided insights into the process and principles of designing for sustainability. Additional cases were selected for a comparison with the core cases, to explore if other grassroots cases demonstrate similar characteristics, and whether the other cases could add to the understanding of alternate practice. A comparison with the canonical design process was done to identify generic findings that cut across the empirical cases. (See Fig. 5).

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[3] Nersessian, "How do engineering scientists think? Model-based simulation in biomedical engineering research laboratories," 2009; Nersessian, *Creating scientific concepts,* 2008.

[4] Braun & Clarke, "Using thematic analysis in psychology," 2006.

[5] Hollan et al., "Distributed cognition: toward a new foundation for human-computer interaction research," 2000; Hutchins, *Cognition in the Wild*, 1995a.

The characterization of the practice of grassroots technology design showed that such design worked by reconfiguring the socio-technical connection, which was found to be very plastic and capable of generating multiple novel designs, but only when the designer started from problem formulation. Further, technology developed for grassroots was found to be aimed at empowering people and sustaining local livelihoods, which is a socio-technical design principle that is wider than the standard model of technology lowering drudgery / cost.

Findings 2 - Cognitive process of design (Ch 7)

Imagination and synthesis are the core cognitive processes in engineering design; formal structures play only subsidiary roles

As current engineering education (EE) focuses on formal structures, and the formal structures mainly support only the detailed design stage in the design process, it is unclear how the design principles and processes, identified in the previous study (Ch 6), could be integrated into EE. To understand how engineering students can start thinking like the designers of sustainable technology, in order to implement sustainable design process and principles, a cognitive historical analysis of the core cases (non-formal and formal design process for the MHP system), was done, to understand the cognitive processes involved in designing such systems, particularly the role played by formal structures. Additional cases were then selected for comparison and a wider characterization. A comparison with the canonical training process allowed for some generalization of the findings, across the results from the empirical cases and the additional cases. (See Fig. 5).

This analysis demonstrated that imagination (mental simulation of material structure and dynamics) and synthesis are the core cognitive processes in engineering design, and the role of formal structures is mostly supportive / supplementary to these core processes. As imagination and synthesis are general cognitive processes, they can include the sustainability engineering principles identified by the earlier analysis, and these can thus be part of EE.

Discussion and implications (Ch 8)

Solving for Pattern is a promising process approach to design technology for sustainability. Implementing this design approach requires setting up of interdisciplinary institutes that bring together design, ecology, engineering, and humanities, to research and promote sustainability engineering

Integrating the findings, an overarching guiding perspective for engineering design for sustainability is developed, borrowing from Wendell Berry's idea of ‘Solving for Pattern’, a design perspective that goes beyond the standard efficiency approach to design. The findings from the studies also indicate that grassroots technology design can provide interesting insights towards developing a new engineering pedagogy for sustainability.

Based on these findings, I develop two policy recommendations to redesign engineering education for sustainability - a) engineering design instruction needs to change, and one operational approach could be Solving for Pattern, and b) engineering selection and training needs to be based on developing imagination and synthesis skills. Bringing these policy recommendations together, I propose an implementation-level recommendation, suggesting the creation of interdisciplinary institutes that bring together ecology, design, engineering, and humanities, to research and promote sustainability engineering. Wider implications of these findings, particularly for research, engineering practice, and pedagogy (particularly case-study-based learning, grassroots projects, and internships), are also discussed.

Table 1: Clarification of concepts and terms used in the document

Term	Meaning
Calibration	Demarcation / measurement of performance parameters against known standards.
Consensus	Agreement on the course of building action or design decision within a team or stakeholders.
Coordination	Communication, distribution, collaboration, and synchronization of design and building work.
Formal structures	Theory, equations, formulas, calculations, graphs, charts, models and other representations based on engineering sciences or mathematics.
Grassroots	The base of the societal pyramid; the large lowest-income strata of society.
Grassroots innovation	The practice of designing innovative solutions to address the unmet needs at the base of the societal pyramid, by individuals or groups from the unorganized sector, who are 'not formally trained' in science and engineering. Such technical/non-technical innovations are being scouted out from the remote interiors of India by the Honey Bee Network. Such innovations are rewarded, recognized, and given further business and Intellectual Property protection support through the National Innovation Foundation, an autonomous body under the Department of Science and Technology, Government of India. See NIF, HBN, SRISHTI, GIAN websites.
Grassroots technology design (as used in this thesis)	Designing of innovative technological solutions to address grassroots needs (unmet by mainstream engineering industry), by individuals or groups, who are non-formally or formally trained.
Idealization	Removing or making abstract parts of a design problem. This is done so that formal structures can be used to generate a model of the design problem.
Imagination	The process of mentally simulating (i.e. activating in working memory) physical structures and their activity/dynamics.
Micro hydro power (MHP)	Electricity generated from flowing water, in the range of 1-100 kW.
Modularization	Separation or isolation of various component assemblies or sub-systems in a technical product or system, for the convenience of design.
Solving for Pattern	A process of solving problems, proposed by American farmer and writer Wendell Berry,[6] where the larger sustainable eco-social patterns within which the design problem is embedded are not adversely disturbed by the design solution.

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[6] Berry, *The Gift of Good Land: Further Essays Cultural and Agricultural*, 1981.

Chapter 1 - Introduction

The practice of building novel structures and artifacts is central to human adaptation. Engineering is the modern version of this adaptive practice. However, it has become clear recently that this adaptive trait is now in runaway mode, as human activity, primarily based on building, has damaged the planet significantly, and has thus pushed every species towards extinction. Changes in our current approach to engineering and design are thus critically needed to address the changing face of global climate and the sustenance of our biosphere, while also addressing the current and future requirements of society. It is imperative that engineering activity delivers sustainable technology that – 1) limits the damage to the environment and the biosphere, including global warming, and 2) bridges the disparities between the developed, developing, and the marginalized. One of the crucial areas where this change is being initiated is the education of 21st century engineers, such that they can design technology for a sustainable way of life on Earth.

1.1 Engineering Education (EE) in India

Modern engineering education started in India during the British rule, with a small surveying school in Chennai in 1794. Engineering colleges were then established at to provide trained surveyors and civil engineers for Public Works Department (PWD), as well as military engineers. All India Council for Technical Education (AICTE) was established in 1945 to plan and coordinate the growth of technical education in India. Post-independence, Indian Institutes of Technology (IITs) were established on the lines on MIT, USA. The Government of India also established Regional Engineering Colleges, now known as National Institutes of Technology (NITs),[7] apart from state-level engineering colleges and private colleges. The IITs and NITs have a more autonomous status, to enable them to meet

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[7] Mashelkar Committee Report, 1998, cf Subramanian, "Engineering Education in India: A Comprehensive Overview," 2015.

international standards. Currently, there are more than 2300 government and private engineering education institutes in India, catering to more than 8,00,000 students.[8]

The quality of academic engagement and infrastructural facilities at these institutes is uneven across the country, and catering to a vast population of aspiring students continues to pose immense challenges to engineering education in India. Particularly, “this massive expansion of engineering education has not been able to provide access to the disadvantaged groups, namely women, scheduled castes and scheduled tribes.”[9] A focus on training for engineering sciences leaves out the training for professional skills emphasized in industrial job interviews. Struggling to teach both these aspects, EE fails to produce students that meet industrial job requirements, which themselves are changing at a much faster pace than education in the current times.[10]

Vision for EE in India mainly aims at converting its demographic 'dividend' to an advantage, by providing a workforce for global industry.[11] The improvements to curricula focus on current needs of industry, while the pedagogical suggestions support educational technology more than opportunities of experiential and active learning.[12]

1.2 Critique of EE across the world

Struggling to address these diverse challenges, engineering education (EE) across most engineering training institutions in India, as well as the world, is only barely acknowledging that sustainability is one of the greatest challenges for engineering and EE today. It is far from addressing this challenge effectively, as is indicated by various scholarly studies, where the sustainability concerns

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[8] Biswas et al., “Profile of engineering education in India: Status, concerns and recommendations,” 2010.
[9] Choudhury, “Growth of Engineering Education in India: Status, Issues and Challenges,” 2016, p 93.
[10] TIFAC, “Technology Vision 2035: Technology Roadmap Education,” 2015.
[11] Subbarao, “India's higher engineering education: opportunities and tough choices,” 2013.
[12] Subbarao, “India's higher engineering education: opportunities and tough choices,” 2013.

are understood primarily in terms of environmental damage and degradation, and socio-economic deprivation and disparity.[13]

Moreover, engineering practice now requires the ability to work in interdisciplinary teams across globally diverse cultures and task contexts, and this requirement is recently getting reflected in EE. However, this is a narrow change, applicable only to the sphere of well-defined problems. This change is not enough to address the wider nature of the sustainability engineering problem, which requires engineering students in developed countries to understand the ill-structured problems related to development. The best students in developing countries, though aware of the problems of the marginalized, are groomed by the EE curricula to tackle the problems of the developed world.[14] Engineering students around the world are thus not trained for sustainability problems, which are arguably the most 'wicked'[15] of all. Critique of engineering education, from a wider scholarly literature, indicates that EE assumes technological knowledge to be limited to engineering sciences and mathematics, and technology is considered to be value-neutral. Design is limited to making techno-scientific calculations, while hands-on field components are mostly missing. Students acquire technical rationality and social disengagement as key aspects of their engineering identity, while lacking a sense of the real nature of engineering practice, and the nature and role of technology. (Ch 2 Literature Review elaborates on this section in detail).

1.3 Reforms in EE

In order to improve EE in general, and to address such critiques, accreditation requirements and expected outcomes of EE programs in many countries have been recently revised to emphasize

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[13] Chandrasekharan & Tovey, "Sum, Quorum, Tether," 2012; Petrina, "The Political Ecology of Design and Technology Education: An Inquiry into Methods," 2000; Stevens et al., "Professional Engineering Work," 2014; TIFAC, "Technology Vision 2035: Technology Roadmap Education," 2015.

[14] Shuman et al., "The ABET "professional skills" – Can they be taught? Can they be assessed?," 2005; Sohoni, "Engineering teaching and research in IITs and its impact on India," 2012; Gupta, "Innovations for the poor by the poor," 2012.

[15] Rittel & Weber, "Wicked problems," 1974.

sustainability.[16] Curricula are being progressively modified to include courses in Sustainability, Humanities and Social Sciences, and Ethics, as well as writing, communication, and interdisciplinary team work, apart from the courses related to environmental sciences and methods.[17] Project and problem-based learning, active participatory learning opportunities, instructional laboratories, learning a second language, and foreign country internships have been found effective pedagogical measures.[18]

1.4 Limitations of the reforms and gaps in the redesign

Nevertheless, these broadening experiences, mostly coming from elective courses in the humanities and social sciences, remain peripheral in the current curricular structure.[19] Even where sustainability concepts and active-learning methods were integrated into the curricula, it was found that there are barriers in re-orienting engineering curricula toward “sustainable” engineering.[20] Pedagogically, the standard instructor-led learning model is not sufficient for developing students as sustainability engineering professionals, as indicated by many studies, including a study of practitioners' responses to a sustainable-design challenge.[21] The reforms are constrained by canonical models of technology and engineering, based on formal and commercial structures.

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[16] ABET, “Criteria for Accrediting Engineering Programs,” 2017; Carew & Mitchell, “Characterizing undergraduate engineering students' understanding of sustainability,” 2002; NBA, “General Manual of Accreditation,” nd.

[17] Biswas et al., “Profile of engineering education in India: Status, concerns and recommendations,” 2010; Carew & Mitchell, “Characterizing undergraduate engineering students' understanding of sustainability,” 2002; Chau, “Incorporation of Sustainability Concepts into a Civil Engineering Curriculum,” 2007; Costa & Scoble, “An Interdisciplinary Approach To Integrating Sustainability Into Mining Engineering Education And Research,” 2006; Huntzinger et al., “Enabling Sustainable Thinking in Undergraduate Engineering Education,” 2007; Mihelcic et al., “Sustainability Science and Engineering: The Emergence of a New Metadiscipline,” 2003; Quist et al., “Backcasting for Sustainability in Engineering Education: The Case of Delft University of Technology,” 2006; Segalas et al., “What Has to Be Learnt for Sustainability? A Comparison of Bachelor Engineering Education Competences at Three European Universities,” 2009.

[18] Chau, “Incorporation of Sustainability Concepts into a Civil Engineering Curriculum,” 2007; Mclaughlan, “Instructional Strategies to Educate for Sustainability in Technology Assessment,” 2007; Shuman et al., “The ABET “professional skills” – Can they be taught? Can they be assessed?,” 2005.

[19] Downey, “PDS: Engineering as Problem Definition and Solution,” 2015.

[20] Huntzinger et al., “Enabling Sustainable Thinking in Undergraduate Engineering Education,” 2007.

[21] Mann et al., “Using phenomenography to investigate different ways of experiencing sustainable design,” 2007.

The appropriate competencies required for sustainability engineering are still not well-understood within the community of engineering educators.[22] Moreover, the interventions are fragmented or segregated, and do not integrate knowledge, skills, and attitudes across disciplines. A focus on developing interventions that address all these in an integral manner are missing. This situation also leads to student identity formation that is merely techno-scientific, which is inadequate for handling complex sustainability problems.

Overall, while the need for sustainability engineering is felt and accepted broadly, it is not very clear how traditional engineering education could be redesigned towards engineering for sustainability.

1.5 The research problem

This background makes it clear that a new approach to sustainability engineering (and its practice) needs to be developed, along with ways to build this approach into engineering education. The limitations of current reforms to engineering education suggest that such a successful pedagogy for sustainability engineering cannot be built around canonical models of EE. Nor can it be built around models offered by contemporary mainstream practice, which mostly do not incorporate sustainability. More promising are successful cases in the wild that demonstrate sustainability, as such cases could offer useful contrast cases, even possibly good role models, to develop a new pedagogy for sustainability engineering.

Following this reasoning, this dissertation undertakes a study of sustainable technology design in the wild, carried out by innovators working at the grassroots. The objective is to understand and make explicit the problem-solving practices, knowledge, skills, and values involved in such design.

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[22] Segalas et al., “What Has to Be Learnt for Sustainability? A Comparison of Bachelor Engineering Education Competences at Three European Universities,” 2009.

Such explicit knowledge of grassroots design practice could contribute significantly towards developing a successful pedagogy for sustainability engineering.

1.6 The thesis and its contributions in brief

This dissertation project, as a systematic effort to study the above research problem, sought to develop an empirically driven characterization and understanding of grassroots innovation (non-formal) and formal (non-mainstream) sustainable technology design practice in the Indian context. The findings from this analysis were then abstracted as core design principles and intervention directions, which are applicable more widely to global engineering education. Building on case study data, this dissertation project makes three key contributions.

1. It develops a design approach and an overarching perspective (principles) necessary for sustainability engineering, by borrowing from Wendell Berry's notion of 'Solving for Pattern'.
2. It characterizes the cognitive process of sustainable technology design that enables such a process and perspective, as well as the role of formal structures in this cognitive process.
3. Based on the above two results, it identifies potential directions for developing a pedagogy of sustainability engineering, where case studies are used to integrate sustainability into specific curricular modules and exercises, and more radically, starting interdisciplinary institutes that bring together research and training across design, ecology, engineering, and humanities.

Further, the contrasting cases of non-formal / non-mainstream technology design developed here offer a new understanding of the nature of mainstream engineering and design, highlighting, and thus creating, the possibility of transcending the limited engineering identity created by mainstream EE.

The dissertation also develops a novel methodology (cross analysis of multiple case studies) to address the open research problem of sustainability engineering education research. It also presents a novel simulation-based probing tool that is especially useful for controlled data collection in design research, as well as ways to convert this simulation into a training tool in the EE context.

Chapter 2 Review of Literature

Reforms aimed at developing an engineering education for sustainability have met with limited success. The reasons for this failure are complex, and require understanding the wider context of traditional engineering education, relevant for understanding and tackling ‘messy’ and ‘wicked’ problems such as sustainability. A review of wider literature was undertaken to identify generic issues related to engineering education (EE) in the context of sustainability, particularly the foundational ideas related to technology and engineering.

2.1 Critique from Engineering Education Research (EER)

Studies in engineering education research (EER) have identified two critical challenges facing EE:

1. Developing students’ ability to address real-world, messy problems
2. Creating student engagement with the broader societal and eco-social ethics and values

Engineering classrooms train students to work with established procedures, and to solve simplified and well-defined textbook problems, based on science and mathematics models. Scholars point out that this training is insufficient to address the ill-structured, complex, and interdisciplinary workplace problems, especially engineering design problems.[23] Dedicated workshops, problem-based

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[23] Dym et al., “Social dimensions of engineering design: Observations from Mudd Design Workshop III,” 2003; Goldberg, “What Engineers Don’t Learn and Why They Don Learn It: and How Philosophy Might Be Able to Help,” 2008; Huntzinger et al., “Enabling Sustainable Thinking in Undergraduate Engineering Education,” 2007; Jonassen, “Engineers as problem solvers,” 2014.

learning, projects and experiential learning, have been recommended to address this issue.[24] But only a few engineering programs have succeeded in running effective courses based on these.[25]

Many scholars, including those in India, argue that an excessive techno-scientific focus in engineering education has led to the exclusion of the social and environmental aspects of engineering.[26] This is detrimental for EE, and some scholars consider this structure as implicitly encouraging a dichotomy between the technical and the social context, and a 'technical rationality'-based problem-solving image of engineering.[27] As a result, social responsibility and professional ethics are limited to safety, and there is little or no understanding of any ‘ethics of care’, or consideration of social justice, based on interaction or collaboration with society.[28] Including ethics as a part of humanities courses in EE has not helped address this issue, and integrating ethics with core engineering courses has been recommended.[29] Critical pedagogy has been suggested as a way to bring in considerations of social justice.[30] Nevertheless, the dominant institutional culture of depolitization is considered to lead to students disengaging from all non-technical aspects of engineering.[31]

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[24] Dym et al., “Social dimensions of engineering design: Observations from Mudd Design Workshop III,” 2003; Jonassen, “Engineers as problem solvers,” 2014; Woods et al., “Developing problem solving skills: The McMaster problem solving program,” 1997.

[25] Cook et al., “Effects of Integrating Authentic Engineering Problem Centered Learning on Student Problem Solving,” 2017; Goldberg, “What Engineers Donʼt Learn and Why They Don Learn It: and How Philosophy Might Be Able to Help,” 2008; Olds, “Engineers of the Future: The Colorado School of Mines' McBride Honors Program,” 1988.

[26] Forbes et al., “Divergent requirements for technical and non-technical coursework in undergraduate engineering programs,” 2017; Olds, “Engineers of the Future: The Colorado School of Mines' McBride Honors Program,” 1988; Sohoni, “Engineering teaching and research in IITs and its impact on India,” 2012.

[27] Bucciarelli, “Ethics and engineering education,” 2008; Felder et al., “The Future of Engineering Education: I A vision for a new century,” 2000a; Vanderburg & Khan, “How well is engineering education incorporating societal issues?,” 1994.

[28] Canney et al., “In their own words: Engineering students’ views on the relationship between the engineering profession and society,” 2013; Canney et al., “Which Courses Influence Engineering Students’ Views of Social Responsibility?,” 2015.

[29] Dunfee, & Robertson, “Integrating ethics into the business school curriculum,” 1988; Herkert & Viscomi, “Introducing professionalism and ethics in engineering curriculum,” 1991.

[30] Catalano & Baillie, “Engineering, Social Justice And Peace: A Revolution Of The Heart,” 2006; Lucena, “The Road Ahead: Questions and Pathways for Future Teaching and Research in ESJ,” 2013; National Academy of Engineering, “Overcoming Challenges to Infusing Ethics into the Development of Engineers: Proceedings of a Workshop,” 2017; Riley, *Engineering and Social Justice*, 2008.

[31] Cech, “Culture of disengagement in engineering education?,” 2013; Cech & Sherick, “Depoliticization and the Structure of Engineering Education,” 2015.

Given any definition of sustainability, these issues need to be addressed, without which engineering education cannot successfully train students to design technology for sustainability.

2.2 Critique from Engineering Studies and STS

Studies of engineering practice, from the domains of Engineering Studies and Science and Technology Studies (STS), establish that engineering is a socio-technical enterprise. These studies show that:

1. Engineering (problems and) products are socially constructed
2. Engineering process is socially distributed and culturally situated
3. Engineering activity (and output) has social responsibility

Firstly, the social and the technical are inextricably tied together in any engineering project, and technology is both "socially constructed and society shaping”.[32] 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'.[33] Vermaas, Kroes, van de Poel, Franssen, and Houkes 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’”.*[34]

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[32] Hughes, “The Evolution of Large Technological Systems,” 1987; Law, “Technology and Heterogeneous Engineering: The Case of Portuguese Expansion,” 1987; Stevens et al., “Professional Engineering Work,” 2014; Suchman, “Organizing Alignment: A Case of Bridge-building,” 2000; Vermaas et al., *A Philosophy of Technology - From Technical Artefacts to Sociotechnical Systems,* 2011.

[33] Law, “Technology and Heterogeneous Engineering: The Case of Portuguese Expansion,” 1987.

[34] Vermaas et al., *A Philosophy of Technology - From Technical Artefacts to Sociotechnical Systems*, 2011, p 95.

Secondly, engineering process is thus socially distributed and culturally situated. It involves teamwork and communication with other engineers as well as non-engineer stakeholders.[35]

> *"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".*[36]

Illustrating this point, Matthias Heymann[37] shows how the superiority of Danish wind technology was derived from social interaction of different groups (particularly windmill artisans and engineers), which was facilitated by journals, social forums, advocacy, test stations, as well as the techno-political settings of Denmark.

Thirdly, engineering activity (and output) has social responsibility. In discussing the social role and responsibility of engineering, George Bugliarello[38] comments that "engineering has performed extraordinarily well in responding to technical challenges, but has shied away from the vigorous pursuit of complex socio-technological 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 socio technological 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".*[39]

This understanding of engineering as a socio-technical enterprise is however missing in the mainstream educational experience of engineering students.

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[35] Bucciarelli, *Designing Engineers*, 1994; Trevelyan, "Engineering Education Requires a Better Model of Engineering Practice," 2009; Vinck, *Everyday Engineering: An Ethnography of Design and Innovation*, 2003.

[36] Trevelyan, "*Reconstructing engineering from practice*," 2010, p 175.

[37] Heymann, "Engineering as a Socio-technical Process: Case-Based Learning from the Example of Wind Technology Development," 2015.

[38] Bugliarello, "The Social Function of Engineering: A Current Assessment," 1991.

[39] Bugliarello, "The Social Function of Engineering: A Current Assessment," 1991, p 81.

2.3 Critique from Philosophy and Politics of Technology

In the analysis of the development of Danish wind technology, Heymann[40] 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)".*

Scholars of philosophy and politics of technology point out that, contrary to its 'objective' image, technology is value-laden, and 'artifacts have politics'.[41] Hence it is necessary to uncover / understand the values both perpetuated and blocked by technology. These studies also argue that technological knowledge is not merely applied science and mathematics.[42]

Furthermore, while it may be assumed that technical values dictate engineering design, it is observed that technical efficiency stands in for economic profit, and thus profit primarily guides mainstream technology development.[43] In contrast, the argument for Appropriate Technology in the 1970s promoted more labor-intensive, and thus income-distributing, values. As reported by Peterson,

> *"The bases of critique applied to industrial countries were that large-scale technologies promoted over-exploitation of natural resources, over-centralization, concentration of political and economic power, less employment because high technology substitute machines for workers, and deskilling of workers because more of the work process is embodied in the movements of the machine rather than in the actions of the operator".*[44]

But "In attempting to redefine technology, advocates of Appropriate Technology were directly challenging the power of those who shaped the hegemonic notion of that subject".[45] Critiqued as non-technology by engineers,[46] the Appropriate Technology movement thus fell back, at least in the

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[40] Heymann, "Engineering as a Socio-technical Process: Case-Based Learning from the Example of Wind Technology Development," 2015, p 487.

[41] Winner, "Do artifacts have politics?,"1980.

[42] Ferguson, *Engineering and the Mind's Eye*, 1994; Schon, *The Reflective Practitioner: How professionals think in action*, 1983; Vincenti, *What engineers know and how they know it*, 1990.

[43] Feenberg, *Transforming technology: A critical theory revisited*, 2002; Mitcham, *Thinking through technology: The path between engineering and philosophy*, 1994; Shiva, "Reductionist science as epistemological violence," 1988.

[44] Peterson, *Appropriate Technology*, 2008, p. 1.

[45] Pursell, "The Rise and Fall of the Appropriate Technology Movement in the United States, 1965-1985," 1993.

[46] Florman, 1981 cf Pursell, "The Rise and Fall of the Appropriate Technology Movement in the United States, 1965-1985," 1993.

USA. Few alternatives to the mainstream models of engineering practice, or ‘doing technology’, are thus available to learn from.

2.4 Critique from Design Studies

Over the last twenty years, interest in design research has shifted from normative studies and nature of problems, to studying designers in their natural settings. These studies have explored the social processes involved in design practice, such as team interaction, communication through objects, gestures, and the role of representations. These studies reveal engineering design as a situated, social process.[47]

Critiquing the idea of engineering design as merely techno-scientific problem-solving, scholars in this domain warn that such a narrow conception will lead to engineering losing its jurisdiction over technology design and development, and engineers' role will be limited to that of mere technical consultants, who only support -- instead of lead -- the design of technology.[48]

2.5 Critique from professional formation studies

Engineering identity is formed largely based on the development of a technical rationality. As a result, students are uncertain about the social role of an engineer, and they consider socio-political aspects as non-engineering.[49]

2.6 Research gap

In summary, this broader scholarly literature (across Philosophy and politics of technology, Engineering studies, Science, technology, and society studies, and Design studies) indicates that

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[47] Atman et al., “Engineering Design Education: Research, Practice, and Examples that link the Two,” 2014; Bucciarelli, *Designing Engineers*, 1994; Minneman, “The Social Construction of a Technical Reality: Empirical Studies of Group Engineering Design Practice,” 1991.

[48] Downey, “PDS: Engineering as Problem Definition and Solution,” 2015; Vermaas, “Design Methodology and Engineering Design,” 2015.

[49] Anderson et al., “Understanding engineering work and identity: a cross-case analysis of engineers within six firms,” 2010; Atman et al., “Enabling Engineering Student Success: The Final Report for the Center for the Advancement of Engineering Education,” 2010; Faulkner, “Nuts and bolts and people,” 2008. .

contemporary EE is based on a canonical approach to technology and engineering, which purports to be value-neutral, and remains limited to ‘safety’ ethics. The sought broadening of EE, through the inclusion of courses in social sciences and humanities, remain peripheral. Current EE structure thus perpetuates societal disengagement, and a design process focused on techno-economic factors, which leads to the formation of an exclusively techno-scientific identity and thinking among students, while the competencies required for sustainability engineering still remain unclear. EE reforms to address these issues are fragmented and isolated, and thus cannot achieve success in addressing the messy complexity of sustainability problems. Current EE practice is thus inadequate to develop an engineering for sustainability.

These critiques of EE and engineering practice are insightful, but they do not provide any systematic ways or operational means to develop a different kind of EE that is oriented towards sustainability engineering. Mainstream practice, which both derives from EE and reinforces it, cannot offer any alternate models. An operational-level way to redesign EE and engineering pedagogy, to support sustainability engineering, can thus only be evolved through the study of successful cases of sustainability engineering 'in the wild'. Since such cases are hitherto unexplored, detailed research studies, and novel research methods, are required.

Chapter 3 Research Approach

Studies of practice provide an evidence-based approach to the design of training for the practice. Examples can be found in both traditional and modern education systems. Curricula and pedagogy for the professions of medicine, agriculture, and business have traditionally been developed from practice. More recently, the modern interdisciplinary curricula and pedagogy for bio-medical engineering were designed by drawing upon ethnographic studies of the practice of bio-medical engineering.[50] These examples indicate that a new evidence-based EE pedagogy for sustainability engineering could be developed similarly through studies of practice, based on the study of unexplored cases of sustainable technology design 'in the wild'.

In the Indian context, Grassroots Innovation[51] (recognized through the National Innovation Foundation) is one such practice in the wild, where individuals 'not formally trained' in science and engineering have designed technology to address their and their communities' needs, which are unmet by formal engineering and industry. A few studies of grassroots innovation have been carried out in the domains of Economics, Business and Development,[52] Innovation,[53] and policy.[54] However, there have been no studies of this practice for developing pedagogical interventions, or understanding the nature of technology design in such cases. Characterization of this non-formal practice, as well as the process of designing such sustainable technologies, provides a promising evidence-based and operational approach to develop a pedagogy for sustainability engineering.

3.1 Research questions

Based on this reasoning, the studies reported here explored the following research questions.

1. What are the key elements of non-formal practice that leads to grassroots innovation (sustainable technology design)? Specific questions include:

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[50] Aurigemma et al., “Turning experiments into objects: The cognitive processes involved in the design of a lab-on-a-chip device,” 2013; Nersessian, “How do engineering scientists think? Model-based simulation in biomedical engineering research laboratories,” 2009.

[51] Gupta, *Grassroots innovation: Minds on the margin are not marginal minds*, 2016.

[52] Cozzens & Sutz, “Innovation in informal settings: Reflections and proposals for a research agenda,” 2014; Dutfield, “Promoting local innovation as a development strategy: Innovations case discussion: The honey bee network,” 2006; Srinivas & Sutz, “Developing countries and innovation: Searching for a new analytical approach,” 2008.

[53] Abrol, “Pro-poor Innovation Making, Knowledge Production, and Technology Implementation for Rural Areas,” 2014; Ahmad, “Policy making for innovations in the informal economy: Insights from National Innovation Foundation and Barefoot College in India,” 2015; Bhaduri & Kumar, “Extrinsic and intrinsic motivations to innovate: tracing the motivation of ‘grassroot’ innovators in India,” 2010; Links et al., “The dynamics of local innovations among formal and informal enterprises: Stories from rural South Africa,” 2014.

[54] Links et al., “The dynamics of local innovations among formal and informal enterprises: Stories from rural South Africa,” 2014; Smith et al., “Innovation, Sustainability and Democracy: An Analysis of Grassroots Contributions,” 2018; Smith et al., “Grassroots innovation movements: challenges and contributions,” 2014.

  i. What are the design principles that underlie sustainable technology design?
  ii. What are the thinking strategies and conceptual models employed in the practice of sustainable technology design?

2. How are these components, (design principles, thinking strategies, and conceptual models) different from formal (mainstream) design practice?
3. What insights could these elements provide for the redesign of engineering curricula and pedagogy?

Chapter 4 Research Design

The practice of grassroots technology design 'in the wild' is an open and unexplored research space, so there are no established methodologies for studying this practice. Case studies are a standard method to understand, and characterize, such unexplored domains. Following this approach, a qualitative, multiple case-study method,[55] using purposively selected cases, was chosen for this research study. I discuss the research design in this section, while the cases are described in Chapter 5.

4.1 The technology context

The primary case of grassroots innovation selected (non-formal Case1: Grassroots Innovator - GRI, recognized by National Innovation Foundation), involved the design of Micro Hydro Power (MHP) generation system (1-100kW), which is a sustainable technology to generate electricity, with no lasting changes made to the environment. The design of an MHP system is not simple, and it is a standard project given to final year engineering students. The 'wild' version of this design thus has sufficient complexity, to provide practice insights into the engineering design aspects of this problem.

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[55] Yin, *Case study research: Design and methods*, 2009.

MHP technology addresses the need for reliable power in grid-deprived remote areas, by utilizing naturally available perennial water streams and mountain gradient. Developing such decentralized mechanisms for power generation, based on these local resources, is a viable and sustainable alternative to centralized grid-based power supply. Unlike mega-power generation based on big dams, such systems do not damage the ecology, and do not displace people from their places, or other species from their habitats.

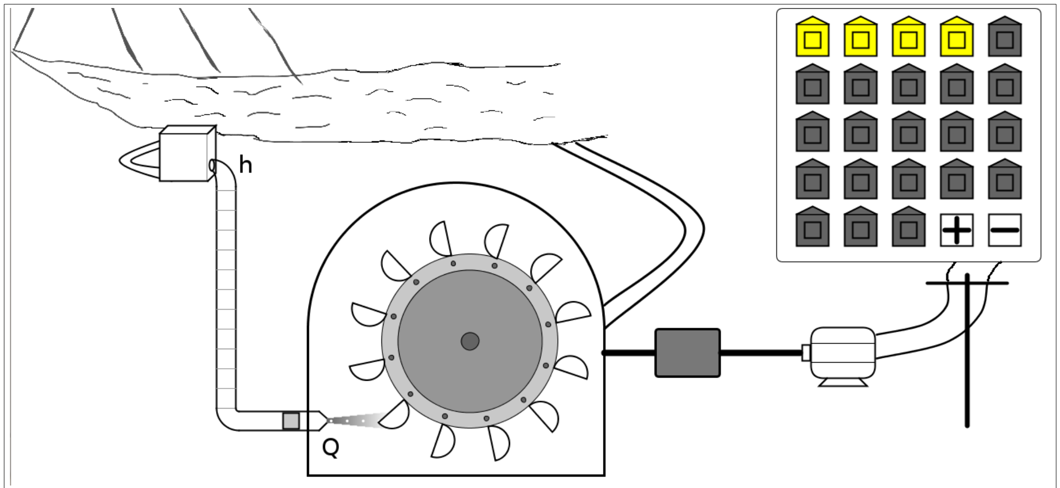

Fig. 3. Schematic of a micro hydro power (MHP) generation system.

The major considerations in the design of a micro hydro power system are: sourcing water, designing a turbine and a generator, coupling the turbine with the generator, and distributing the generated power. (See Fig. 3).

Water is sourced and diverted or stored. A pipeline, laid along the slope from the storage, is fitted with a nozzle, which shoots a jet of water on the turbine blades. The vertical distance (the ‘head’ h) between the storage and the nozzle, and the flow rate of water (Q), principally govern the theoretical (hydraulic) power output from the source of water at any site. These factors also influence the choice of turbine type and the details of turbine design.

4.2 Data collection

To understand the formal approach vis-a-vis the non-formal practice, the case of a formally-trained engineering practitioner designing the same technology at the grassroots was then identified (Case 2: Engineering Professional - EP). To contrast practice with the education scenario, a case of students designing MHP system as a final year engineering (capstone) project was also identified (Case 3: Engineering Learner(s) – ELs).

The empirical data collection for these core cases were based on primary sources (interviews, observation, artifacts, simulation data), as well as secondary sources (photos, videos, and reports including journal publications, brochures, and news articles), given that the technology design process was historical and extended over time for the core cases.

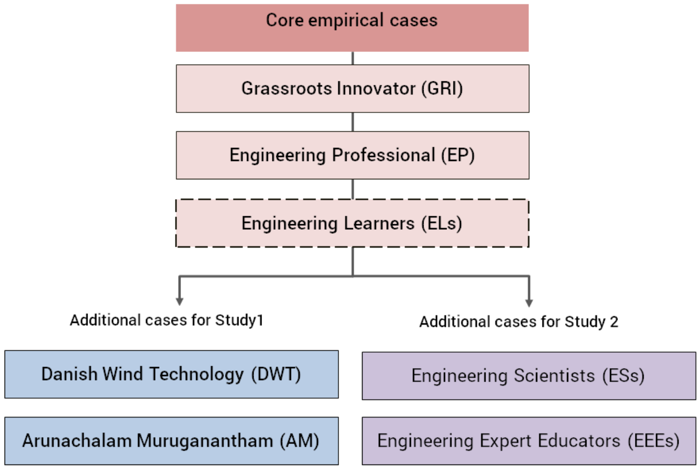

Fig. 4. Cases purposively sampled for this thesis.

Further, in order to probe and compare the design thinking systematically and in a controlled way, across both formally and non-formally trained designers, a simulation system with visual and numeric modes was also developed. This system helps overcome some of the limitations of design research methods such as verbal protocol, content analysis, process isolation, and situated lab studies. Real-time interaction data were collected using screen and sound capture (video recording), touch screen and mouse interactions (as data logged automatically at the back end), and probing interviews (audio recording).

Additional cases (See Fig. 4) based on secondary data were then selected and analyzed, to understand the empirical data better, to articulate the findings, and to find converging generic principles.

4.3 Data analysis

Cognitive historical analysis[56] and thematic analysis[57] were the primary methods used to analyze the cases and to interpret data. This approach generated a qualitative understanding. An analysis based on a ‘practice lens' was developed, using themes of design episodes, transitions, and design considerations (Study 1). In the next study, a second analysis based on a ‘cognitive’ lens was developed, where cognitive processes and their configurations were identified (Study 2). (See Fig. 5 for the analysis machine).

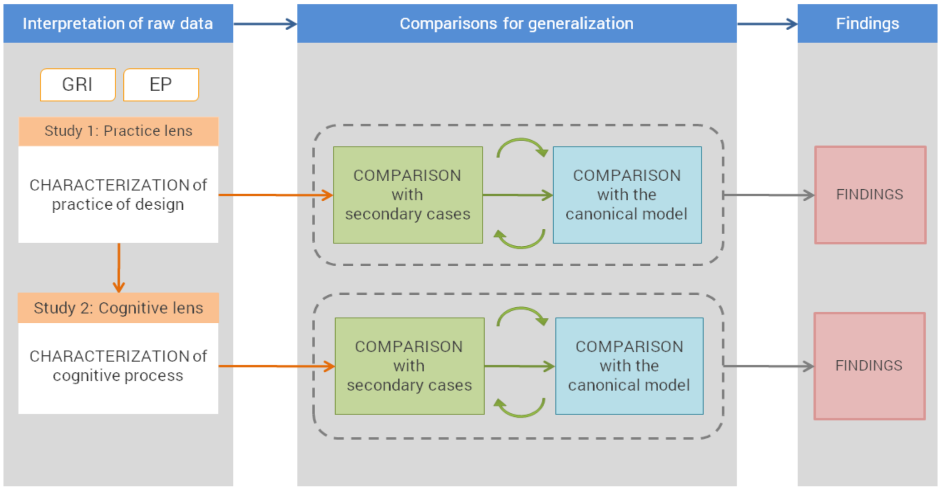

Fig. 5. Multiple case cross analysis design followed in this thesis.

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[56] Nersessian, *Creating scientific concepts*, 2008.
[57] Braun and Clarke, “Using thematic analysis in psychology,” 2006.

Based on the findings from these two analyses, implications were drawn for a possible pedagogy of sustainability engineering. Distributed cognition[58] was the primary theoretical framework used for studying the design process and thinking.

4.3.1 The analysis machine

4.3.1.1 Study 1

The two core empirical cases of GRI and EP were first described and characterized. The student (ELs) case was not characterized in detail at this stage, as the data supported findings about students reported in the literature. In order to get better insight into the open problem of sustainability engineering, more cases were then selected, and contrasted with the core cases. The first such case was the development of Danish Wind Technology, a sustainable technology developed largely by artisans and craftsmen who were untrained in formal engineering (Case 4: Danish Wind Technology - DWT). The second case was a non-formal grassroots innovator recognized by NIF, who designs and supplies low-cost sanitary napkin-making machines to rural production houses run by self-help groups of women (Case 5: Arunachalam Muruganantham - AM). Along with the core cases (1-3), these cases (4, 5) allowed for a better characterization of sustainable design and manufacturing processes as well as business models. The cases converged, to offer generic design principles for sustainability engineering. (See Chapter 6, also Date & Chandrasekharan, 2017 – based on cases 2, 4, 5).

4.3.1.2 Study 2

The findings from the first analysis provided some design principles, but no systematic way to incorporate them in the EE curricula, which are based on formal structures. Changing the EE curricula thus requires understanding the cognitive roles formal structures play in engineering design, and how the design principles identified by study 1 relate to these cognitive roles played by formal structures. This required a second analysis based on a cognitive lens, as the first analysis did not

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[58] Hutchins, *Cognition in the Wild*, 1995a; Hutchins, “How a cockpit remembers its speeds,” 1995b; Hollan et al., “Distributed cognition: toward a new foundation for human-computer interaction research,” 2000.

provide an understanding of the thinking processes involved in sustainable technology design, or contrast this with thinking processes involved in mainstream engineering. This understanding would be necessary to identify how pedagogy needs to be redesigned at the operational level to support sustainability engineering. Towards this, the primary data were analyzed again, to characterize the cognitive process involved in MHP design. A canonical model of the cognitive training process assumed in standard EE was contrasted with this characterization.

The historic and interview data were limited for developing this analysis, and a novel simulation tool was designed to probe design thinking in a controlled way across formally and non-formally trained designers (See Chapter 7, also Date & Chandrasekharan, 2018 – based on case 1).

In order to validate the results from the analysis based on the core cases, three more cases were used in Study 2 as contrast cases, where the technology problems were open-ended (unlike MHP, which is a 'solved' problem for formal science / engineering). The first two of these were cases from a team of engineering scientists at a leading engineering research laboratory in India, working on the cutting-edge problem of sustainable Fuel Cell technology (Case 6: Engineering Scientists – ESs). The third was the case of an open-ended estimation problem in technology design, solved by engineering educators who were also experienced as practicing engineers (Case 7: Expert Engineering Educator(s) – EEEs). These protocol analysis cases were drawn from a reported study.[59] The characterization of the cognitive process in design, based on the primary cases (1-3), was cross-validated with these additional cases (6, 7). (See Date & Chandrasekharan, 2017 June – based on cases 1-3, 6, 7).

Overall, the research design was data-driven, rather than driven by a framework or theory. The understanding generated was qualitative, based on the interpretation of the findings, but these findings were cross-validated using additional cases.

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[59] Kothiyal et al., "“Hearts Pump and Hearts Beat”: Engineering Estimation as a Form of Model-Based Reasoning," 2016.

Chapter 5 Case Studies

This chapter describes the cases in brief. The core case of engineering learners (ELs) was not analyzed in detail for this thesis project, and only a basic outline of this case is provided here.

5.1 Primary / core cases

5.1.1 Case 1: Grassroots Innovator – GRI

Fig. 6. GRI's domestic MHP system, also drives a flour mill.

GRI initially developed an MHP system for his own household in the Western Ghats mountains, where grid-based power was erratic in the rainy months of Monsoon, but perennial water streams were plenty. Educated in a local-language school up to grade ten, GRI had no formal knowledge of MHP science or engineering. He started designing the system with a bicycle dynamo, and progressed to building his own permanent magnet generators, while also trying out a variety of fans and wheels, finally designing his own turbine wheel. (See Fig. 6). He then established his own business, and has now installed more than 300 MHP systems for coffee estates, communities in reserve forests, temples, as well as individual houses and small outfits, across many states in India.

5.1.2 Case 2: Engineering Professional – EP

Fig. 7. EP's multi-purpose electromechanical MHP system.

EP, a formally trained civil engineer from one of the leading institutes of technology in India, constructed his first power generation system for his professor, who was conducting research in the high altitude Himalayas. Lack of funds in the research budget made it necessary for him to design a low-cost MHP system, which was modeled after a traditional water mill running on perennial water streams. This experience initiated EP on a sustainable technology journey, where he worked with NGOs and communities in remote mountains to build MHPs and provide power. (See Fig. 7). He designs formal-knowledge based Pelton and Cross flow turbines, but people and the context are also central to his designs.

5.1.3 Case 3: Engineering Learner(s) – ELs

ELs, a team of students designing technology for their final year engineering (capstone) project, started with the idea that they could provide domestic power in areas that face power scarcity, by storing rain water on roof-tops of multi-storeyed buildings, and using it to drive a pico or micro hydro power system. Based on their formal training, they decided to build a Pelton type turbine. They looked up the design specifications on the Internet. Since both budget and workshop facilities were limited, they modified the given design, and manufactured a turbine with the materials available to them. (See Fig. 8). The system functioned well, but generated less power than what was projected by the technical calculations they started with. One of them, who later went on to use a Computational Fluid Dynamics (CFD) software, felt that if the CFD software was available during the project, their system would have been much better.

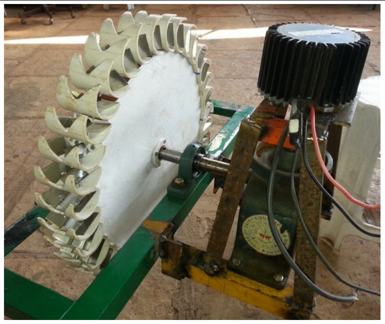
Fig. 8. ELs' pico hydro power system for engineering project.

5.2 Additional / secondary cases

5.2.1 Case 4: Danish Wind Technology – DWT

Denmark has a long history of using wind turbines, such as Poul la Cour's 'Klapsejler', to generate DC power, and Johannes Juul's turbine near 'Gedser' for AC power. During the energy crisis of 1970s, many countries, such as Denmark, France, Germany, UK, USA, and the Netherlands, struggled to develop modern wind technology as a source of


Fig. 9. Carpenter Riisager's wind turbine.

power. Of these, the Danish wind turbine systems were designed in collaboration between artisans and craftsmen (starting with carpenter Christian Riisager and blacksmith Karl-Erik Jørgensen, and others) and this design proved to be the most successful, while the designs based on purely formal approaches failed, despite high-tech competence and high capital investments. (See Fig. 9).[60]

5.2.2 Case 5: Arunachalam Muruganantham – AM

AM, educated up to grade eight and working in a fabrication workshop, found that his wife and sisters could not afford to use sanitary napkins during their monthly menstrual periods. Thinking that a sanitary napkin was a mere cotton pad that was sold at an exorbitant price, AM tried to develop a low-cost sanitary napkin himself. After many personal struggles and design challenges, he solved the napkin design problem, and went on to develop a low cost machine to make sanitary napkins. This machine is now used by women self-help groups (SHGs) (See Fig. 10)[61] all over the world, to produce napkins locally, at prices as low as Rs. 2 for a piece, compared to at least Rs. 10 charged by multinational companies. He is now recognized world over (Time ‘Most Influential People’ 2014, ‘Padmashree’ from the Government of India) for his 'white revolution', as his design has improved hygiene, health, women empowerment and communities, and has provided livelihood to many poor rural women.


Fig. 10. Manufacturing of sanitary napkin in SHG.

5.2.3 Case 6: Engineering Scientists – ESs

A team of engineering scientists based at a research lab in India is developing cutting-edge Fuel Cell technology for futuristic applications. Though the team is formally trained, in the case of fuel cell technology, the engineering theory, i.e. the formal structures, are not entirely known, and the

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[60] Image © 1996 Copyright The Electricity Museum, Bjerringbro, Denmark.
[61] Image © Jayashree Industries.

operational principles and configurations are still in the process of development. During the design process, they came across and solved several technical problems, related to various components and processes.

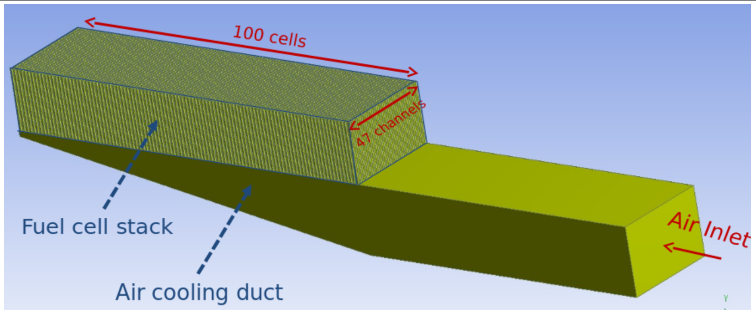

Fig. 11. A Fuel Cell cooling duct modeled in CFD.

In this study, two such problems, and the process developed to address these, are discussed: i) the design of a cooling duct for the fuel cell stack, ii) the design of a rubber gasket for the fuel cell plate. (See Fig. 11).

5.2.4 Case 7: Expert Engineering Educator(s) – EEEs

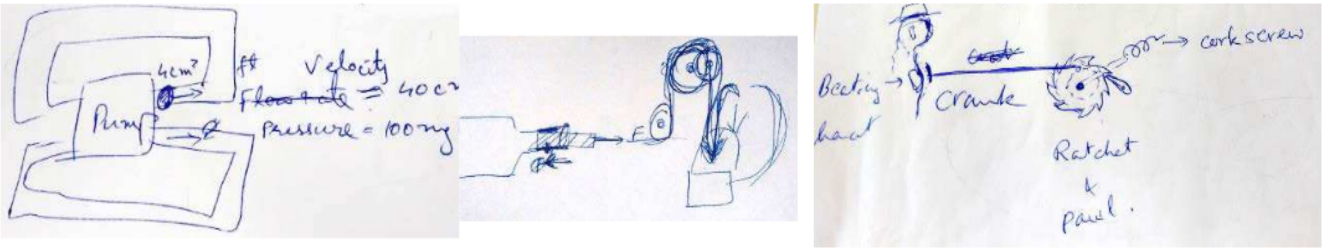

Fig. 12. Heart modeled as pumping and beating, Kothiyal et al., 2016.

Kothiyal and colleagues[62] conducted an empirical study of the engineering estimation process, in which two expert engineering educators (EEEs) were independently given the problem of estimating whether the power produced by the human heart could run a wine opener, to open a wine bottle. Interestingly, both the experts started by generating different analogies and different design approaches to address this task, but both arrived at similar estimates through this process. One of the experts (E1) modeled the heart's pumping function, and thought of the heart as a pump, while the other

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[62] Kothiyal et al., "“Hearts Pump and Hearts Beat”: Engineering Estimation as a Form of Model-Based Reasoning," 2016.

(E2) modeled the beating function, and thought of the heart as driving a ratchet. (See Fig. 12). Only in the last stage of the estimation process did one of them perform formal calculations.

Chapter 6 Characterization of sustainable grassroots design practice

The analysis of multiple case studies started with the primary cases of practice (GRI and EP). For each of these cases, key design episodes were identified from raw data, and the features of transitions from one episode to the next were captured. The design considerations during each episode, and between the transitions, were also identified. Based on this episode level data, a description of the design practice was constructed.

These narratives were then analyzed and interpreted, to characterize the grassroots technology design practice (using the Practice lens). For this, first the characterizations developed (case studies) were validated using secondary/additional cases (DWT and AM). Secondly, the findings from these cases were compared to the canonical design process (the linear model learned in engineering classrooms). Based on this analysis, a general model of the design process was developed.

This chapter is organized as follows:

1. **Characterization of grassroots design practice**: Description and analysis of the design process of the non-formally trained GRI, and the formally-trained EP.
2. **Comparison with additional cases**: Validation of the two primary cases, through a comparison with the design process of secondary / additional cases (DWT and AM).
3. **Comparison with the canonical model**: Comparison of the findings from these analyses with the canonical understanding of the design process (the linear model learned in engineering classrooms).

6.1 Characterization of grassroots design practice

6.1.1 GRI's design process

6.1.1.1 Description of GRI’s design process

The analysis of data on the historical trajectory of GRI's designs, over a period of five years, shows certain landmark stages or distinct episodes of design prototypes, culminating in his final working design. These are as follows:

Lighting a torch bulb: Though he was not trained in formal engineering, GRI was familiar with bicycle DC dynamo as a simple power-generating device. He had also visited a mega hydro-power generation facility, and was thus aware that the force of water could be used to generate power. Further, he was familiar with a (water-driven) fan-like device used in paddy fields in his area, which automatically beat drums at night to keep away wild boars. Combining these ideas and devices, GRI attached plastic cups to a bicycle rim, such that the rim rotated when water hit the cups. The dynamo shaft attached to the rim rotated as well, creating DC power that lighted a small torch bulb.

DC storage and more power: GRI then replaced the bicycle dynamo with a DC dynamo used in motor vehicles, and added a DC storage battery, to store the generated power. He needed a stronger bicycle wheel to handle more water and generate more power. For this, he tried several versions and materials, and various wheels he got from scrap markets. Finally, with the help of a carpenter, he designed a spokes wheel similar to a bullock-cart wheel, later replacing the material with MS steel. After experimenting with many angles and shapes of the blades, and comparative testing at a single site, he finalized his most effective design.

AC power: DC power had to be converted to AC to run the household gadgets. Instead of doing this conversion, GRI replaced the DC dynamo with an AC alternator.

Grid quality power (constant voltage): When a TV or a blender was running, switching the gadgets on or off seemed to create a problem, as the voltage dropped. He needed to ensure that changes in the electric load did not affect the voltage, or damage the gadgets and the hydro power system. He tried three different solutions over time to resolve this problem: a booster (transformer), an Automatic Voltage Regulator (AVR), and a flywheel. For him, the most effective solution was the flywheel, which balanced the RPM of the turbine wheel when the load dropped, keeping the voltage and frequency of the alternator constant.

Innovating further through his many experiments and prototypes, GRI finally had a complete working system after five years, which supplied grid-quality power. He continued technology development, to support a grain-grinding mill working on the turbine, and to provide power to remotely-located telecom towers. In order to generate power even with a very low RPM, he also started designing and building his own permanent magnet generators.

6.1.1.2 Analysis

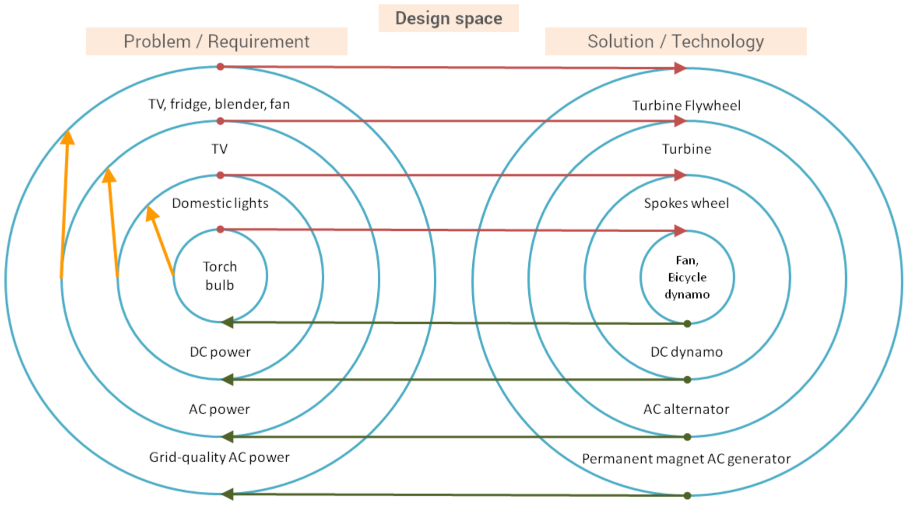

Fig. 13. GRI's socio-technical design process.

For GRI, as the gadget requirement goes from simple to complex in the problem space (See Fig. 13), it gets addressed in the solution space (red arrows). The built technology acts as a prototype, as well as a representation, to address the requirement (green arrows) at the next level (blue arrows). The design space expands spirally, as complex solutions emerge from technically simple designs.

6.1.1.3 Insights from GRI's design process

GRI's understanding of the problem and solution starts with the social, and the technical is cumulatively added to address these. He uses heuristics, thumb rules, and trial & error methods the most, while formal explicit knowledge is never used.

GRI's each design episode is a complete solution. The previous solution space acts as a prototype for him, and also as a representation, for the new problem space, and includes the problem context. He thinks using the components, prototypes, and the problem context. His design solution progresses from technically basic to advanced, but stays simple and uncomplicated, and diversifies into many design solutions.

GRI's understanding of power, and various components, is mostly qualitative and experience-based, rather than quantitative and theoretical.

6.1.1.4 Insights from GRI's design considerations (principles)

GRI's design considerations are mainly qualitative. For instance, functionality is understood in terms of power for a particular gadget, performance is understood in terms of flickering of the bulb (indicating the voltage fluctuation). The basic rule is 'simplicity'.

In GRI's design, the technical, material, ecological, and social considerations intertwine. This leads to diverse sustainable solutions, such as using surplus electricity to power street lights, or diverting it to dry clothes in a heating room.

GRI values availability, affordability, access, local self-sufficiency and sustainability, beyond technical input-output efficiency or high quality of power. For instance, to generate safe, grid-quality power, a flywheel is concluded to be better than an efficient Automatic Voltage Regulator. Even the flywheel may be optional if the requirement is only lighting, where grid quality is not a requirement.

6.1.2 EP's design process

6.1.2.1 Description of EP’s design process

The analysis of raw data shows that there are four key transitions in EP's design process, across different sites, and over a period of several years. These shifts are seen to be carried into subsequent designs as guiding principles. They are thus not mere site-specific customizations.

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 Himalayan region of a protected National Park. Due to lack of funds and the remoteness of the site from the state power grid, EP extended traditional water mills installed on perennial streams in the region, to develop a water turbine. EP's modified design increased the shaft's rotations per minute (rpm) by ten to twelve times, from 300 to about 3000. This turbine was coupled to an alternator that charged a DC battery.

Pelton turbines and Digital Load Controllers (DLC): From his formal training, EP knew 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. One such was the Pelton-based micro hydro power system EP built in 2005, for two tribal villages in a remote area 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 25kW 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.

Cross flow turbines and heating coils: When good flow of water was available throughout the year, EP designed cross flow turbines, which work well at low heads. A cross flow turbine is simpler to design, fabricate, and maintain. Though less efficient, it is less expensive, and cleans itself. 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.

Electro-mechanical power generation: In 2006-9, EP's NGO was an implementation partner for a renewable energy ministry project in a remote mountain district. EP designed 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. Further, EP designed scaled-down machinery for livelihood generation, drudgery reduction, and income earning based on local natural resources, such as wool washing, wool carding, spinning, oil milling, flour milling, and rice threshing.

6.1.2.2 Analysis

In the initial projects, EP was primarily focused on the technical aspects of providing electricity. Community aspects were not a part of the design. Across the key transitions, 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. EP's recent projects are conceived on the model of electro-mechanical livelihood projects. Close interaction with the eco-social context, to identify the grassroots needs, expanded EP's problem formulation from techno-economic to socio-technical, and 'clarified the task' to include the qualitative, rather than only quantitative. He now questions generating power only to upload it to the grid for the cities, when, as his model demonstrates, so many income generating activities can be supported with the power in remote rural households.

> *"How can anybody come and install a micro hydro without knowing the local needs? Then, we have to ask.. for so much of money, you set up a micro hydro and put electricity in the grid, I said, "how does it help people?" [EP]*

His design is not a process of refitting the previous solution by tweaking only the detailed design. The kind of detailed design calculations (use of engineering knowledge) that is called for depends on the design decisions taken at the earlier stages; it is thus not as direct / obvious as applying formulas to a textbook problem with given technical parameters.

Starting with the need, context, and bringing the society-technology connection into the design process, expanded EP's design space. This enabled him to design the most suitable and sustainable technology solutions.

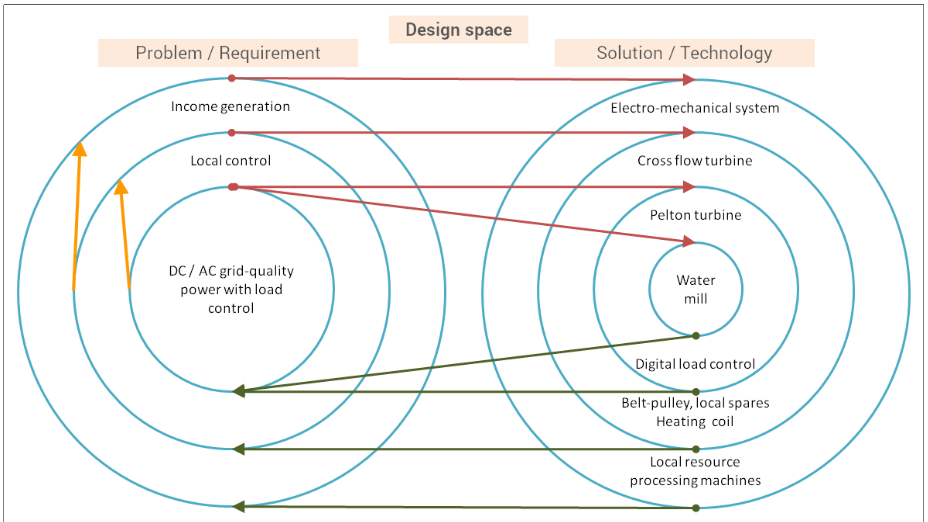

Fig. 14. EP's evolving socio-technical design process.

For the power problem, a complete solution is developed in the solution space (See Fig. 14, red arrows). The technology acts as a prototype to address the requirements (green arrows) at the next level (blue arrows). As the understanding of power requirement goes from technical to socio-technical (expanding circles in the problem space), the complex technology is simplified (expanding circles in the solution space). The design space expands spirally, and socio-technically sustainable solutions emerge.

6.1.2.3 Insights from EP’s design process

EP’s understanding of the problem starts with the technical, and expands to the social. This expansion influences all stages of design. The nature of requirements is complex, non-technical, and only slowly become explicit. (Note that EP is a designer external to the context, unlike GRI).

EP’s solutions progress from complete but complex and technical, to complete and simplified eco-socio-technical. The previous solution space acts as a prototype for the new problem space, and includes the context. Despite his formal knowledge, a large role is played by heuristics, thumb rules, and trial & error methods.

With experience, EP’s conceptual understanding of power progresses from quantitative, formal, and theoretical, to qualitative. This progression to ‘expertise’ is counterintuitive to prevailing notions, which consider expertise as a shift from qualitative to quantitative.

6.1.2.4 Insights from EP’s design considerations (principles)

EP’s design considerations are partly qualitative, where functionality is seen as power to generate livelihood, and performance is understood as sufficient perennial power. The basic design rule for EP is also ‘simplicity’, and it goes closer to the user and user context progressively.

EP’s design considerations also intertwine and strengthen the technical, material, ecological, and social, leading to alternate, sustainable designs (multi-business application of power) vis-à-vis a mega dam. He also strongly opposes uploading power back to the grid, for the benefit of the cities, while leaving the producers exploited.

EP now values access, local self-sufficiency, income generation, and sustainability, over exclusively technical criteria such as input-output efficiency or technical sophistication, optimization, or standardization, even though he is trained for these.

6.2 Comparison with additional cases

GRI and EP’s grassroots MHP technology, based on water, delivers non-polluting (clean) and a renewable (green) energy. The MHP technology thus inherently satisfies the requirements of ‘sustainability’ in its canonical sense. Could it be that the design process and considerations in this grassroots design appear sustainable only because MHP is essentially a sustainable technology?

Furthermore, the MHP systems are necessarily decentralized in design and operation. As a result, they help bring out the advantages of decentralized design and operation. But would decentralized design be advantageous in general, say for sustainable product design and manufacturing?

It could also be argued that the MHP system is a relatively simple technology, based on classical science. Design processes and principles derived from these cases may thus not be applicable to situations where technological solutions are not known, or are complex and cutting-edge, and are spread globally. Also, the salient processes and principles may be entirely different in interdisciplinary teams.

This begs the question: is this characterization of grassroots technology design practice limited in scope, and a result of the choice of cases? Are there other grassroots cases which demonstrate similar characteristics? Can other cases add to this understanding of alternate practice? To answer these questions, I explored additional cases of technology design practice beyond MHP: 1) A case of cutting edge technology design (Danish wind technology; DWT), and 2) A case of product design (Low cost sanitary napkin making machine; AM).

6.2.1 DWT design process[63]

The development of Danish wind technology (DWT) was initiated during the energy crisis of 1970s, by artisan and craftsmen, and supported by the entire country, where different stakeholders contributed to the design in various ways. Big companies in America and Germany, such as GE, were also trying to develop wind turbine designs. These two design efforts developed in parallel, and this case thus allows exploring the process of designing a cutting-edge technology, to develop a renewable energy alternative.

6.2.1.1 Description of DWT design process

Based on the Gedser turbine by Johannes Juul, carpenter Christian Riisager and blacksmith Karl-Erik Jørgensen started building simple wind turbines. They conceptualized and prioritized different parameters of wind power generation, compared to theoreticians' emphasis on high efficiency and optimization. With a limited theoretical background, but practical experience and off-the-shelf inexpensive parts, Riisager produced a reliable 22-kilowatt turbine, and sold more than fifty of them in a few years. Danish people who were looking for independent electricity sources, even at a higher price, purchased these wind turbines. With the government offering subsidy, this market grew. But only licensed turbines could avail of the subsidy, so manufacturers worked with government test stations to standardize these designs for licensing. With a rise in demand, which 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.

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[63] This historic case-study analysis is based on secondary data, and published work: Garud & Karnoe, 2003; Heymann, 2015; Kamp, 2008; Kamp 2004; Karnoe, 1990.

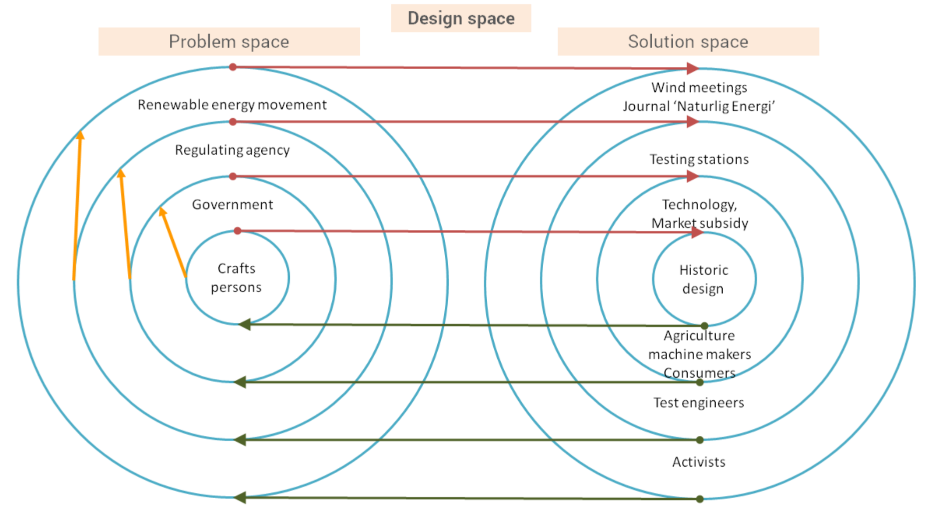

Fig. 15. The multi-stakeholder driven bottom-up process of DWT design.

This was a bottom-up design process that was supported socio-technically by diverse stakeholders. (See Fig. 15). This sustainable technology proved to be more robust, cost-effective, and longer performing, but less efficient, than those developed by leading R&D labs in USA, Germany, and the Netherlands. Given these performance advantages, the Danish designs won out, as in the 1980s, when major wind turbine installations were put up in California, 45% were supplied by about six commercial manufacturers from Denmark.

6.2.1.2 Insights from DWT design process

The DWT problem formulation included multiple technical and socio-political aspects, for the development of a cutting-edge renewable technology. The design process was bottom-up and step-by-step, and not top-down and theory-driven. Hands-on artisans conceptualized and prioritized different parameters of wind power generation, vis-a-vis theoreticians' emphasis on high efficiency and optimization. The earlier designs such as scientist Poul la Cour's 'Klapsejler', and electrician Juul's Gedser turbine, were used to think with, and build upon, by carpenter Christian Riisager and blacksmith Karl-Erik Jørgensen. These different socio-technical players, with their interconnections and diversity of knowledge, needs, and ideologies, led to a wider design space.

6.2.1.3 Insights from DWT design considerations (principles)

DWT designers valued robustness, and longer performing, cost-effective designs, over more efficient wind systems developed by leading R&D labs, based on formal engineering practices. Early installations gained them valuable long-term feedback on use, across decentralized and diverse users.

The DWT design process created space for diverse considerations, from stakeholders such as agricultural machine companies for manufacturing, government credit and market subsidy, government test stations and licenses, citizen forums like 'wind meetings' and the journal ‘*Naturlig Energi*’ for political and technical support. They together enabled a robust and eco-socially sustainable ‘for-profit’ business model.

6.2.2 AM’s design process[64]

The design of a machine to develop low-cost sanitary napkins, by AM, another grassroots innovator and entrepreneur recognized by NIF, allows understanding the design of a product, in the context of a 'solved problem', where the existing technological solution was not inherently clean or green (unlike the MHP system). AM's alternative design generated a disruptive product that led to equity and flourishing, design features now recognized as central to sustainability.

6.2.2.1 Description of AM’s design process

Despite extremely difficult technical, economic, and social challenges, (including ostracization by his village, and his wife leaving him for a while), AM succeeded in building a set of four simple machines to manufacture low-cost napkins of good quality. Knowing very well how the poor struggle for income generation opportunities, he went on to set up rural manufacturing units using his machines, involving women self-help groups. His designs are now open source, and machines are functioning in rural areas all over the developing world, where the napkins are made and sold by women.

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[64] This historic case-study analysis is based on secondary data.

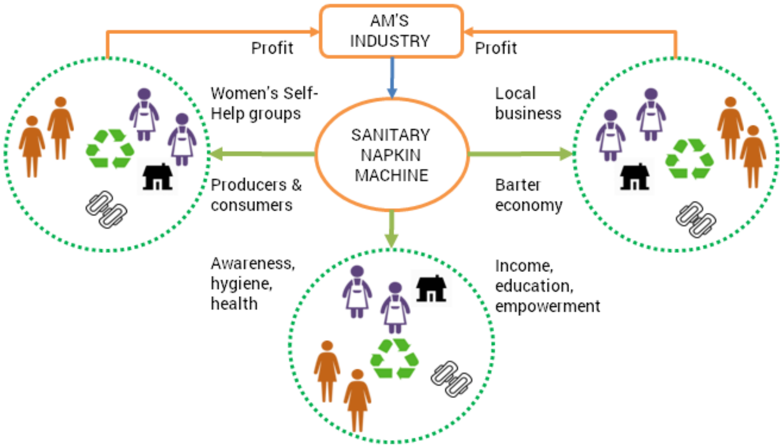

Fig. 16. AM's decentralized production business model.

This decentralized design approach has led to better hygiene, health, and women empowerment, compared to the design and distribution of napkins by multinational companies, which follows a highly centralized and linear design approach. (See Fig. 16 and 17).

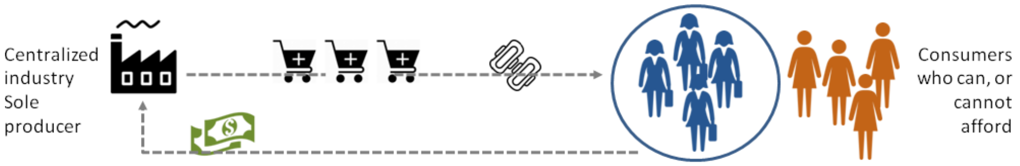

Fig. 17. A contrasting mainstream model of centralized production – business.

6.2.2.2 Insights from AM’s design process

At the problem formulation stage, AM’s technology design process started from a social-economic need, which the designer recognized from his personal experiences. He was drawn to the design problem by a sense of empathy, and a deep understanding of the socio-economic context.

Also, his process was not limited by standard engineering frameworks. AM’s design started from requirements, but went all the way to manufacturing. He thus created a novel combination of two standard design processes, which are usually considered separate in current engineering: product and manufacturing. This novel combination widened AM's design space, allowing him to create a disruptive, original, and socially beneficial business model.

In AM’s design, labor is used as design feature, and not treated as a ‘bug’ to be corrected or removed. The embodiment design (form) of the machines is modular, and aimed at aiding human actions, which allows distributing the work between humans and machines in a complimentary manner. This leads to local economies where the producer and consumer are situated in the same environment, which prompts them to work together to find ways to keep it clean, through efforts such as developing ways to make the napkins biodegradable. This is in direct contrast to centralized approaches that seek to build huge machines that limit the role of people, a key feature of current manufacturing. This structure also requires building vast supply chains, to transport products from centralized manufacturing facilities to faceless consumers. This in turn de-couples the producer from the consumer, and leads to systems where the producers are focused on maximizing production regardless of the need, and take no responsibility for environmental damages caused by their product.

6.2.2.3 Insights from AM’s design considerations (principles)

AM values socio-economic access, affordability, and hygiene in designing the sanitary napkins. This in turn leads him to design the napkin machines, where his design considerations are ease of operation, and semi-automation, not the maximum number produced per hour.

AM values livelihoods as sources of independent income generation, and thus he designs technology to support or add to livelihoods, especially for rural women. He designs such that small self-help groups of women can establish their own manufacturing set-ups using his machines. This business model fits the women’s way of life, schedules, and even allows barter, while letting them control the production, depending on their market. AM prioritizes decentralization of production as well as distribution of wealth in his design. For this reason, he values open access to his design. His design principles across the product, its production, distribution, and consumption thus emphasize creating awareness, hygiene, livelihood, and empowerment.

AM's design considerations reflect a wider socio-technical and network approach to efficiency, incurring less social and environmental costs, compared to a purely input-output efficiency approach. Moreover, there is a concern for the local environment, which is shared by both producers and consumers (unlike in the case of the MNC). This concern is reflected in ongoing efforts to make the napkins biodegradable.

6.2.3 Validation insights from the additional cases

Insights about design process and principles for grassroots technology design, from comparison of the primary empirical practice cases with the additional cases, are summarized as follows. (See Box 1 and 2).

Box 1: Insights about grassroots technology design process

The grassroots technology design process

- Is situated in users' eco-socio-economic context. This illustrates, and makes explicit, the complex and socio-technical nature of design requirements.
- Is distributed across artifacts and stakeholders, as well as constant improvements and iterations based on feedback.
- Addresses complex societal requirements/needs and multiple technology solutions. These illustrate, and make explicit, the flexibility or plasticity of society-technology connections.
- Involves design experiences – where many alternate ways emerge to connect technology and society – that coagulate as a perspective in the designer, guiding future designs.

Box 2: Insights about grassroots technology design principles

The grassroots technology design principles

- The technology is optimized eco-socio-technically, based on user context, rather than based on theory and input-output efficiency. Examples include:
  - Powering street lights, instead of using heating coils as dummy load. This saves wastage of surplus power, and avoids releasing of hot water back into the stream.
  - Designing to allow for diversion of water for irrigation in the summer, indicating that local priorities are a part of the optimization, and communities have control over their resource use, thus limiting consumption accordingly.
  - Using simple components and locally available spares. Optimize for local

independence in low-cost maintenance and repair.

- Decentralized business models create / support local jobs or livelihoods, rather than centralized mass production.

6.3 Comparison with the canonical model

6.3.1 The canonical model of design process

6.3.1.1 Description of the canonical design process

According to the canonical model of the engineering design process:

> *"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".*[65]

Along these lines, many models of design process have been described, prescribed, and referred to in engineering design education, depicting a minimum of the following stages: Task clarification, Conceptual design, Embodiment design, Detailed design, and Documentation (See Fig. 18). The task clarification stage aims to arrive at a list of quantified technical task specifications from an identified need, problem, or a potential new application of science. The concept design stage focuses on the technical concept of the function to be performed, while the embodiment design stage captures 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 reconsiderations at the previous stages. This feedback possibility gives the model some iterativity, but the nature of design process it depicts is primarily linear.

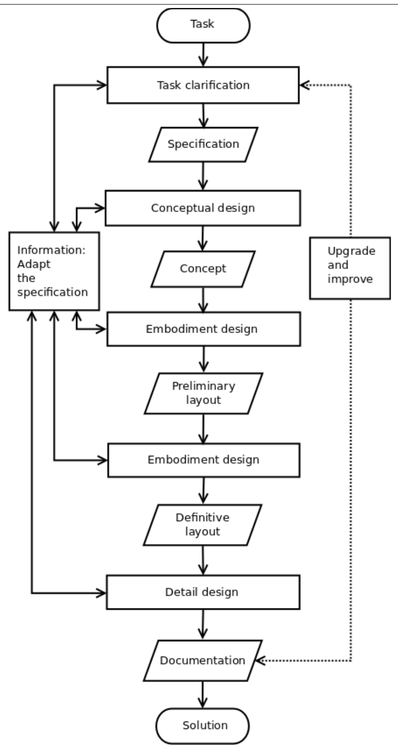

Fig. 18. Canonical design process.
(Based on Pahl & Beitz, 2007).

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[65] Pahl & Beitz, 2007.

6.3.1.2 Current critique of the canonical model

This canonical linear model of the design process has been critiqued by many scholars. In design, problem understanding and solutions are seen as emerging together[66] and designers do not necessarily perform all the activities outlined in the canonical process.[67] Practicing engineers draw alternate diagrams of the process, and emphasize users, problem scoping, and communication far more[68] than captured in the linear model. Experts revisit 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".[69]

Even though such a detailed critique exists, Haik and Shahin 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".*[70]

According to a model of 'requirement identification and application activities' developed by Chakrabarti et al.,

> *"... 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".*[71]

Chakrabarti et al. point out, however, 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".*[72]

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[66] Lawson, *How Designers Think*, 2006.
[67] Jonassen, "Engineers as problem solvers," 2014.
[68] Mosberg et al., "Conceptions of the Engineering Design Process: An Expert Study of Advanced Practicing Professionals," 2005.
[69] Mosberg et al., "Conceptions of the Engineering Design Process: An Expert Study of Advanced Practicing Professionals," 2005.
[70] Haik & Shahin, *Engineering Design Process*, 2011, p 231.
[71] Chakrabarti et al., "Identification and application of requirements and their impact on the design process: a protocol study," 2004, p 36.
[72] Chakrabarti et al., "Identification and application of requirements and their impact on the design process: a protocol study," 2004, p 22.

In a rare lab study comparing individual designers on a given mechanical design task, the (formally trained) m-designers' design process mostly followed the linear process model, and they clarified the task extensively before moving on to conceptual design, while the (practically experienced, non-formally trained) p-designers did not.[73]

6.3.1.3 Comparing the canonical and the practiced design processes

Despite formal knowledge that assumes the canonical process, the analysis of EP's practice indicates that his design process is not linear within a design episode. It jumps ahead – and skips or combines stages. For example, it combines the conceptual and embodiment stages in the traditional water mill EP modified. This is similar to results from other studies of practice.[74]

As per the canonical process, the task specification, once frozen, is expected to disconnect / disengage from the context during the rest of the design process. In EP's case, the interaction with context is not limited to only an initial task specification stage, it is seen to influence all the stages.

The necessary interaction between the social and technical illustrated by EP's designs, and the reflective feedback across similar design problems, is not captured in the canonical design process, even though it depicts a feedback loop that is limited to a particular design episode. Task specifications, as advocated by the canonical model, may thus work as a mechanism to externalize the social factors from the engineering problem space.

EP's notion of optimality evolves, to include social and environmental factors. This shift rejects the optimality assumed by the input-output efficiency model, and thus goes beyond customization, which is based on some canonical model considered as standard.

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[73] Gunther & Ehrlenspiel, “Comparing designers from practice and designers with systematic design education,” 1999.
[74] Jonassen, “Engineers as problem solvers,” 2014.

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. This is not the case in standard engineering design practice, as the different design components are modularized, and the experiences are thus scattered, thus not coming together as integrated perspectives. As Engineering Education follows the canonical model, students would also have such scattered experiences. Unless trained, they may take many years to understand the need and method to develop integrated design perspectives, if at all.

6.3.1.4 Comparison insights about the canonical design process

The canonical design process model / diagram misses the non-linearity inherent in design, the complexity of problem formulation, as well as the continuous role of context, i.e. the society-technology connection (focuses only on a quantified ‘task specification’). It emphasizes a purely techno-scientific design process, following a linear and assembling structure, as opposed to the evolving and spiral structure seen in the grassroots cases.

Furthermore, the canonical design guidelines imply that the central design values are: functional / performance efficiency, cost, the economies of scale / centralized mass production, and profit. They raise the question of optimization ‘for which context?’ (See Fig. 20).

6.3.2 The canonical design principles

6.3.2.1 Description of the canonical design principles

Pahl and Beitz[75] describe technical function, cost, and safety as the general objectives of any design process (See Fig. 19).

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[75] Pahl & Beitz, *Engineering Design: a systematic approach*, 2007.

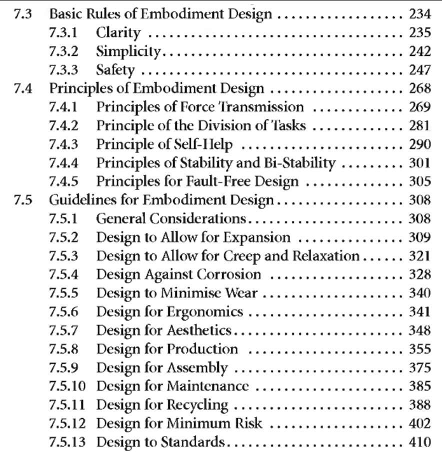

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Fig. 19. Canonical design principles. (Pahl & Beitz, 2007).

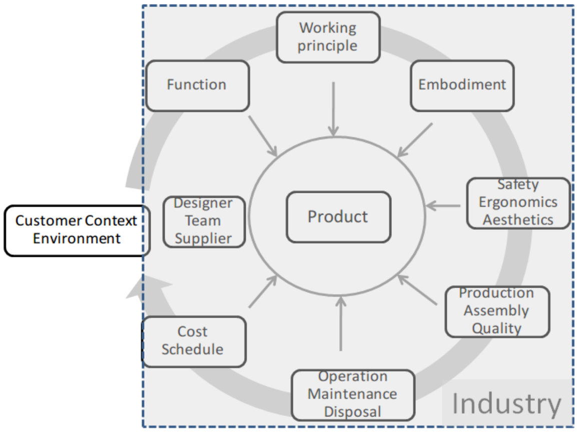

Fig. 20. Based on canonical design guidelines. (Based on Pahl & Beitz, 2007).

Further, they suggest that requirement guidelines are generated from considerations and constraints of ergonomics, aesthetics, production, schedule, maintenance, and so on (See Fig. 20), and these “should be treated as *guidelines* throughout the design process”.[76]

6.3.2.2 The canonical and the practiced design principles

EP’s design considerations indicate that he uses the formal technical guidelines, which are a part of his training, while retaining a constant focus on the context of the users and the environment. For example, despite a high formal value placed on standardization to reduce costs, he does not opt for standardizing his designs or components, as such standardization would be at the cost of designs that cater to the specific needs of a community.

6.3.2.3 Comparison insights about the canonical design principles

The canonical design guidelines discuss many design principles, but do not provide an overarching perspective that compels a designer to understand these principles in the context and the environment of the end user. The canonical design principles thus remain optionally followed. Lacking an overarching design value and perspective, these principles do not address the constraints at the user-end.

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[76] Pahl & Beitz, *Engineering Design: a systematic approach*, 2007, p 44, italics original.

6.4 Generic insights from the comparisons

The insights about design process and principles for sustainable technology design, from the primary empirical practice cases, as well as from comparison with the additional cases and the canonical models are summarized as follows. (See Box 3 and 4).

Box 3: Insights about sustainable technology design process

The sustainable technology design process
• Does not start with a given ‘frozen’ task specification; nor does it end with calculations to arrive at technical specifications. • The conceptual and embodiment stages are not always distinct, or based on formal knowledge. • The interaction with the socio-ecological needs expands the task specifications and design space. • The design space is widened by changing the socio-technical connection. This understanding of the socio-technical connection, as it being 'plastic', enables design innovations. • Context helps in quickly narrowing down designs, to appropriate options.

Box 4: Insights about sustainable technology design principles

The sustainable technology design principles
• The design is focused on user needs and their eco-social context, rather than on technical input/output efficiency and performance optimization, which work as a proxy for the production / business context of the manufacturer, and a centralized revenue model. • The design is guided by the formulated problem, and is not ‘customizing’ a standard one-size-fits-all solution. • The design values local control, maintenance and repairs, thus enabling self-sufficiency, rather than dependence on trained personnel or services from far away. • The design is decentralized to family or group/community size, rather than centralized for a profit-driven factory model, which requires hundreds of employees to congregate in one place, and thus leads to relocation of communities. • The design is oriented more towards livelihood / income enhancement / employment, than convenience, comfort, or luxury. The design also does not seek to develop technology for speed / power to save cost / drudgery.

6.5 Findings 1 - Characterization of sustainable grassroots design practice

This analysis leads to the following characterization of the sustainable practice of grassroots technology design.

a) Plasticity of socio-technical connection in the technology design process enables innovation.

b) The socio-technical connection is plastic, but only when the design process starts from need (problem) formulation.[77]

c) The idea of optimality goes beyond that assumed by centralized efficiency and revenue models, to include social and environmental factors, such as the long-term well-being of all species.

d) Sustainable technology aims at empowering people at the grassroots and sustaining their local livelihoods, a design principle that goes beyond drudgery / cost reduction.

6.6 Conclusion

Findings from the grassroots design cases indicate that current technology design works with a limited notion of sustainability, driven by the narrow idea of input-output efficiency, as illustrated by models such as ‘trade-offs’, ‘triple bottom line (people, planet, and profit)’, and ‘eco-efficiency’[78]. This technocratic conception of sustainability also underlies the discourse of sustainable development, which is presented as “maximum sustainable consumption of optimally efficient technologies.”[79]

In order to reorient technology design towards sustainability, it is necessary to move beyond this technocratic view. Scholars have suggested ethics, benign design, inclusive and affective design,

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[77] Date & Chandrasekharan, “The Socio-Technical Connection is Plastic, but Only When Design Starts from Need Formulation,” 2016.

[78] Schmidheiny, *Changing Course: : A global business perspective on development and the environment*, 1992.

[79] Davison, *Technology and the Contested Meanings of Sustainability*, 2001 cf Lau, 2010, p 254.

and value-sensitive design as some of the approaches that could help broaden engineering design beyond this technocratic view.[80]

Findings from this study broaden the notion of sustainable technology design, to include social and ecological relationships, and enabling a flourishing of all. The findings also suggest, in a bottom-up manner, the overarching perspective of ‘sustainability as flourishing for all’ as a design guideline. In chapter 8, I integrate these ideas into one possible operationalized approach and perspective, termed ‘Solving for Pattern’. This approach provides an operational way to arrive at sustainable technology design, in both practice and education.

Chapter 7 Characterization of the cognitive process of sustainable grassroots design

The analysis in the previous chapter identifies ‘enabling thriving or flourishing for all’ as a critical component of engineering for sustainability. This design principle / perspective thus needs to form a central component of engineering practice, and engineering education (EE) could pave the way for this critical change. Current engineering education, however, is focused entirely on theoretical knowledge and formal structures,[81] particularly the application of engineering sciences and mathematics. As these appear to be the distinguishing feature of engineering design, the focus may seem justified. Scholars from STS, Engineering Studies, and Design Studies however have critiqued the excessive and exclusive emphasis on formal structures as undue, and sometimes detrimental to engineering (design) education.

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[80] Erlandson, *Universal and accessible design for products, services, and processes*, 2007; Friedman et al., “Value sensitive design: Theory and methods,” 2002; Holt & Barnes, “Towards an integrated approach to “Design for X”: an agenda for decision-based DFX research,” 2010; Robison, “Design Problems and Ethics,” 2010.

[81] Theory, equations, formulas, calculations, graphs, charts, models and other representations based on engineering sciences or mathematics.

7.1 Scholars’ view of EE emphasis on formal structures

Scholars point out that engineering design is more than instrumental reasoning, and involves negotiation and uncertainty.[82] Eugene Ferguson[83] also argues that design is not primarily a problem in mathematics. Scott Minneman[84] comments that understanding ‘expertise in design’ as “performing operations on abstract engineering representations” is a limited view, which is upheld only because other aspects of design may not be as easy to model. Charles Eastman[85] comments that going to the bottom of engineering sciences is not how designers arrive at wider choices or better design options. Based on empirical studies, these scholars emphasize the role of intuition, non-verbal thought, perception, manual skills, and experience. While these studies argue against the emphasis on formal knowledge in engineering design education, the literature does not sufficiently elaborate the role that formal structures actually play in technology design.

In order to develop engineering education (EE) curricula and learning processes that systematically incorporate sustainability principles, the assumptions underlying current curricula and pedagogy need to be analyzed. One way to do this is to examine the cognitive justification for EE's current focus on formal structures, particularly how this focus contributes to engineering design. A clear characterization of the *cognitive* roles formal structures play in the *process* of engineering design is thus needed.

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[82] Bucciarelli, *Engineering philosophy*, 2003; Schon, *The Reflective Practitioner: How professionals think in action*, 1983.
[83] Ferguson, “The Mind’s Eye: Non-verbal Thought in Technology,” 1977.
[84] Minneman, “The Social Construction of a Technical Reality: Empirical Studies of Group Engineering Design Practice,” 1991.
[85] Eastman, “Explorations of the cognitive processes in design,” 1968.

7.2 Design cognition view of cognitive processes in engineering design

An analysis of related literature[86] indicates that design thinking, and the cognitive processes of design, have been studied extensively, especially for improving design practice and education. Most such studies start from an 'information-processing' model of cognition, using this model as the basis of design cognition research. There is a recent turn in this literature towards more contemporary cognition approaches (distributed, situated and embodied cognition), but these frameworks have not been systematically applied to develop an understanding of the cognitive processes and mechanisms underlying design. In particular, these wide and disparate studies have not shed much light on the roles formal structures play in design.

7.3 Characterization of the cognitive processes underlying grassroots technology design

In order to get more clarity on the role formal structures play in design, I analyzed the practice data using a cognitive lens, to characterize the cognitive processes in grassroots technology design cases and three other cases, including the canonical one. In the following sections,

1. I describe and analyze the cognitive process of design of non-formally trained GRI, and formally-trained EP (Characterization of the cognitive processes of grassroots technology design).
2. I expand on the insights / preliminary findings from this analysis using two additional cases, one from engineering sciences and the other from a study of engineering estimation.

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[86] Buchanan & Margolin, *Discovering design: explorations in design studies*, 1995; Chandrasekaran, "Design problem solving: A task analysis," 1990; Cross, *Engineering design methods: strategies for product design*, 2000; Dym, "Teaching design to freshmen: Style and content," 1994; Eastman, "New directions in design cognition: Studies of representation and recall," 2001; Goel, "Dissociation of design knowledge," 2001; Goldschmidt, "Visual analogy – a strategy for design reasoning and learning," 2001; Lawson, *What designers know*, 2012; Newell & Simon, *Human problem solving*, 1972; Schon, *The Reflective Practitioner: How professionals think in action*, 1983; Stauffer & Ullman, "Fundamental processes of mechanical designers based on empirical data," 1991; Zimring & Craig, "Defining design between domains: an argument for design research á la carte," 2001.

3. I compare the findings from these analyses with the canonical understanding of the cognitive process underlying engineering design (as depicted by the training model in engineering classrooms), and the cognitive process of design of formal engineering students (Els), to present some generic findings.

All the cases are illustrated using process diagrams, showing the different cognitive process components and configurations involved in the design process in each case.

7.3.1 GRI's cognitive process during design[87]

GRI had no formal training, but he knew from experience that electricity could be generated (bicycle lamp would be lit) by rotating the shaft of a dynamo. His first idea for rotating the shaft using hydro power was derived from a simple traditional contraption (sometimes called the ‘water ghost’) used in the local paddy fields. GRI combined the two gadgets to light a simple torch bulb, using water power. GRI’s cognitive process of design thus started from artifacts in the world.

GRI then built his first prototype by imagining a combination of the two real-world artifacts. Here the cognitive process moves from the designer to the prototype (see Fig. 21, pink arrows from the designer to the prototype). GRI's prototype works as an implemented external representation, of the structures and functions he has generated through imagination. As he built the designs and ran them in the real world, the prototypes interacted with his internal image and mental simulations (of the movements of his designs). This interaction process further modified his understanding of the problem and the components, which changed his mental image, allowing him to imagine further design elements (see Fig. 21, pink arrows from the prototype to the designer).

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[87] See Chapter 6 for the design process details underlying this cognitive process analysis.

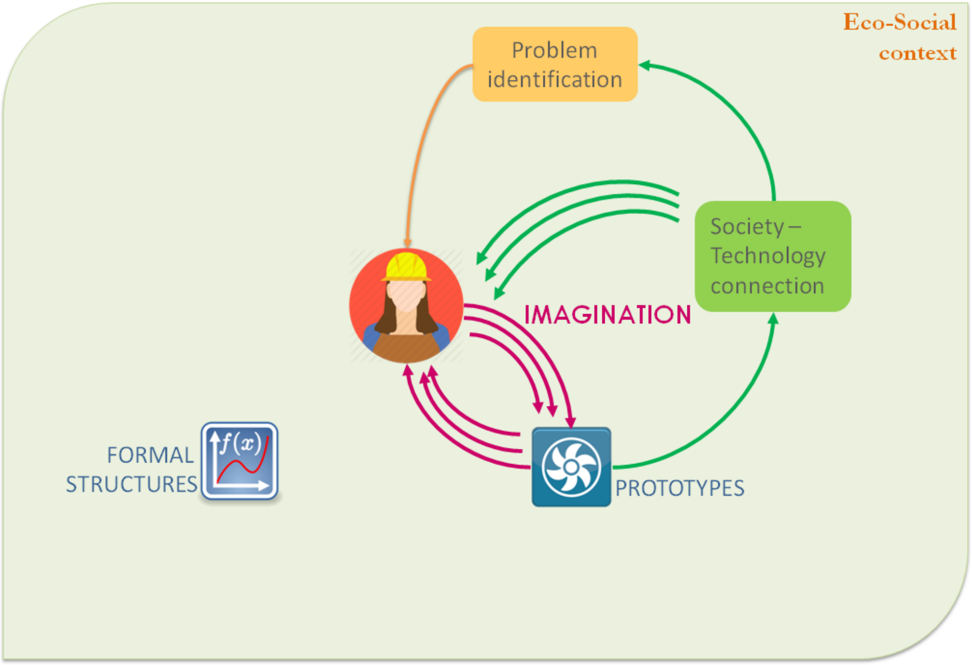

Fig. 21. GRI's cognitive process - Socio-technical connections (green arrows) were integrated with the cognitive process throughout the design cycle, prototypes worked as models for GRI's subsequent designs (pink arrows to and from prototype to designer), no formal structures or representations were used.

Importantly, as GRI engages with the need to power more gadgets, (bulbs, TV etc.), the socio-technical context becomes part of his imagination process. Here the cognitive process moves from the prototype to designer again, but differently (See Fig. 21, the wider loop of green arrows from the prototype, to S-T connection, through amber arrow from problem to the designer).

As can be seen from the figure and the case study presented earlier, GRI's design process does not progress with the help of formal structures, theories and equations. Nor does he make drawings or theory-driven calculations. In terms of the cognitive process, he uses each prototype as a model to think with, to understand the problem space and to generate solutions. The lack of formal knowledge constrained GRI in terms of speed, as it took him years to arrive at a working and stable system. He could not hasten this process through ready comparisons and calibration using formal structures (See Fig. 21, formal structures are excluded). Instead, he improved by trial and error. Also, GRI could not design or modify his components by using abstract criteria offered by formal parameters. He needed to build the components and run the entire system, to test the effect of any changes in design.

However, this slow process allowed him to frame and scope the problem differently from a formally trained engineer. In particular, he does not externalize the eco-social aspects from the problem formulation. These aspects, which are always present for him, allows him to define, test, and select the functions to be performed by his system in socio-technical terms, rather than componentized or idealized technical terms. He also thinks with components and particular designs, which embed, and thus allow him to manipulate in imagination, their problem contexts and requirements.

7.3.1.1 Role of formal structures in GRI's design

GRI understood and selected his design components on the basis of their situated performance in practice, which allowed him to understand the inter-relations and constraints of the components. He learned about the functioning of the components not in terms of abstract science and modularized behavior, but through constant testing, which allowed him to develop an integrated conceptual understanding of the components. Due to this, he did not need to invest extra effort to integrate various bits of knowledge about the components. His process indicates that prototypes are not mere instantiations of formal structures, they are situated systems that embed multiple interactions and constraints, and also work as systems to think with. The real-world testing possibly also allowed him to develop tacit knowledge to deal with 'scale effect' issues, as indicated by his reference to ‘percentage’ change in generated power or efficiency.

GRI designed by balancing the inputs and outputs of the various components within the overall constraints, rather than by making calculations to arrive at exact individual component specifications.

In the search for alternatives and components, GRI was exposed to formal engineering terminology used to describe the phenomena and concepts. This exposure slowly aided him in communicating with and about formal structures. For example, he probably started talking about (and measuring exactly) RPM, as he started interacting with formally trained engineers and engineering students.

7.3.2 EP's cognitive process of design[88]

Despite his formal training, EP's design episodes indicate that his cognitive process of design did not begin with or remain restricted to formal structures. The rotation of a traditional mill by stream water allowed him to imagine an alternate embodiment of the (formal) conceptual turbine. It acted as a prototype he could work with, and allowed him to arrive at a design, through modification of the blades of the traditional mill. His formal knowledge enabled him to compare the traditional mill with a formal system, and calibrate its RPM for the required power generation, using an alternator. (See Fig. 22).

In the next episode, EP went beyond formal structures to innovate for the eco-social context, when he designed a system using two different alternators: one for the low and the other for the high water discharge period. EP had a head start because the problem triggered formal knowledge about turbine types (which is generic), and it offered him a way to structure the problem very quickly. But it did not help him consider the aspects not included in formal structures (such as maintenance), and he had to discover these for himself after the design, to move to better solutions.

EP then extended his design to functions beyond lighting bulbs, to the running of income generating machines, by designing two different outputs from the same hydro turbine: electric power and mechanical drive.

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[88] See Chapter 6 for design process details underlying this cognitive process analysis.

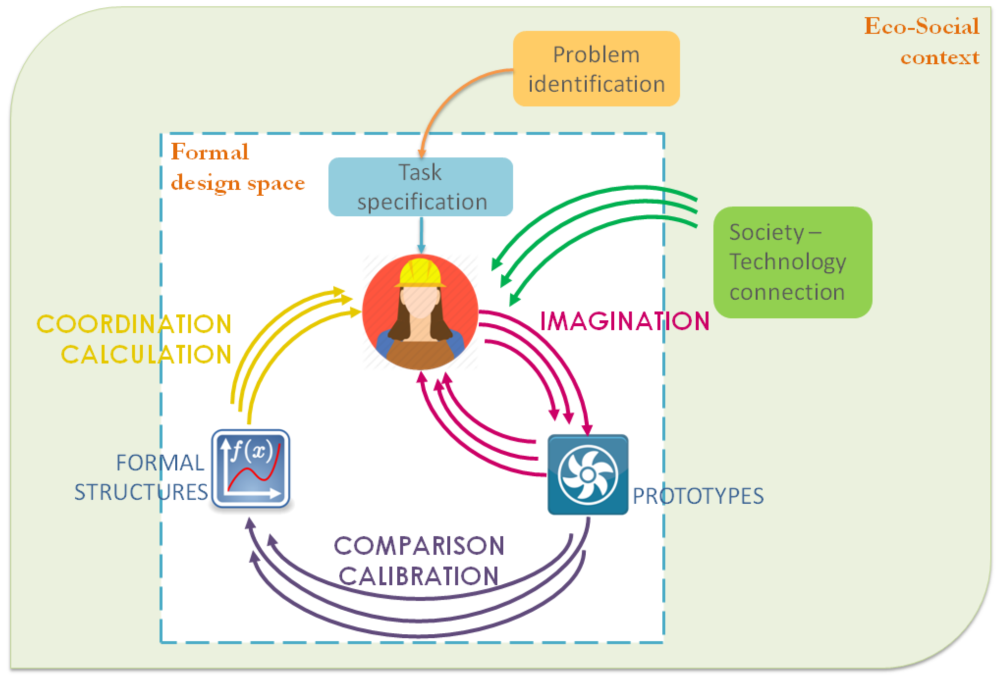

Fig. 22. EP's cognitive process - In each of EP's design episodes, socio-technical connections (green arrows) were progressively integrated with the cognitive process, prototypes worked as models for his subsequent designs (pink arrows to and from prototype to designer), and were also compared and calibrated with the formal structures (or representations where formal structures were not available) (purple arrows from prototypes to formal structures). Formal structures were also used for calculations and coordination (yellow arrows from formal structures to designer). EP did not start the design process with formal structures. Imagination allowed for a widening of the design space, beyond technical input-output parameters, to include the eco-social context.

While EP uses his formal training, engagement with local context and conditions broadened his problem definition (See Chapter 7, also Date & Chandrasekharan, 2016). In each of his design episodes, imagination allowed for a widening of the design space, beyond technical input-output parameters, to include the eco-social context.

7.3.2.1 Role of formal structures in EP's design process

EP could gather wider information about site conditions using formal representations such as survey maps and hydrological charts (which provide an across-time and deep structure understanding, which is not readily available from observations). Comparisons with formal structures, such as turbine performance charts, friction loss studies, and research literature, allowed him to validate and calibrate his prototypes, as in the case of Pelton and Cross flow turbines. Formal structures also allowed him to clearly communicate the design specifications, to the fabricators, as well as while purchasing various off-the-shelf components, including generators.

In the simulation Task 4 (numeric), where given a head (4 m) and discharge (16.25 lps), EP was required to estimate the power generated in the virtual MHP system. Despite the formal knowledge of theory and idealized equations, EP automatically followed an imagination process, where he mentally simulated the head and discharge, in terms of their real-world implications for the design of various parts of his system (rather than generating numeric inputs to churn out a numeric output, of the amount of theoretical power generated). His mental model of power generation thus consists of the complex interactions of various design considerations, of which the head and discharge values are only one part. This mental model is not made up of idealized parameters and formal structures.

EP also referred to many thumb rules that he follows, for detailed design of components, as well as for testing and verification. These indicate how his procedural, heuristic, experiential, and locally situated knowledge have come together, and have crystallized over the years into declarative, but largely qualitative, knowledge. This integrated qualitative knowledge plays the largest role in his design process; the formal knowledge only plays a subsidiary role.

7.3.3 Cognitive processes in grassroots technology design

The two cases (non-formal innovator, formally-trained engineer) together demonstrate that imagination (mental simulation of structure and dynamics) is the key mental process driving the generation of the material form, and not parameter-based thinking. The following general conclusions can be made about grassroots technology design from these analyses.

The cognitive process of design starts with external artifacts, and not formal theoretical structures, including calculations. Both GRI and EP used structures in the design context, to build with and to think with. Their prototypes were themselves external representations of the structures and functions they mentally imagined. Both GRI and EP developed and used thumb rules and heuristics. Their procedural, heuristic, experiential, and locally situated knowledge came together in the design process. They also used their judgment of the water flow and its variations, as well as local knowledge. Their design process was cognitively situated in the location, and the society that they worked for and with.

Lack of formal knowledge made it necessary for GRI to conduct many trials, and carry a range of spares, whereas EP could save experimentation time, effort, and cost using formal knowledge. In the design episodes where EP's cognitive process of imagination was supplemented by formal structures, he could calibrate, calculate, and optimize his design. In a particular design episode where EP's cognitive process was driven by formal structures alone, it quickly imposed a structure on the ill-structured problem. But in this case, his design considerations remained technical, and sustainability was attempted as an afterthought or an add-on.

The Designer – Prototype – Formal structure relationship is thus best understood as a distributed cognitive system, situated in the larger and local eco-social context. Based on this analysis, I propose the following schematic model of the cognitive processes of sustainable technology design at the grassroots. (See Fig. 23).

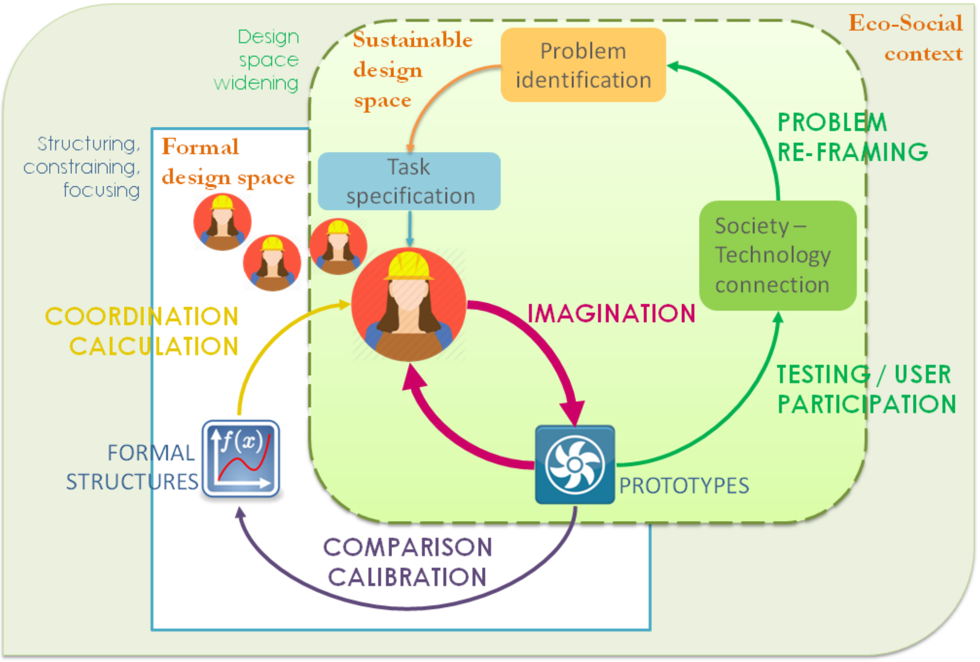

Fig. 23. Cognitive processes in grassroots technology design-
Imagination widens the design space, to include the eco-social.

The above model (See Fig. 23) shows imagination as the core cognitive process (pink arrows). Given the central role of imagination in the cognitive process (rather than formalization), both the formal and the non-formal (eco-social) can be brought together and synthesized by imagination, to play key parts in the design space, thus widening it beyond the formal design space (into sustainable and formal design space). This synthesizing role of imagination enables the society-technology connection to be an active and constant component of the iterative cognitive process (green arrows). Evidence for this wider process comes from the participation of various stakeholders (including the users) in the testing of the prototypes, as well as the re-framing of the problem with the help of the prototype (porous boundaries of the sustainable design space indicate its openness to the eco-social). These aspects provide the potential to develop a design process where ‘solving for pattern’ design principles play a central role, and thus lead to technologies that promote sustainability, which is at the core of the design.

In the case of EP, the imagination process is *supported* by the interaction between formal structures, the prototype and the designer. This process provides structure to the problem space, through comparison, and calibration, of different designs, and helps constrain and focus the search for solutions within the wider design space. Once the initial framework is set up using imagination, detailed design is speeded up through calculations based on formal structures, for cases where such modeling is possible. Coordination with stakeholders becomes easier as well, because formal structures provide a standard framework for reaching consensus on the design specifications.

7.4 Comparison with additional cases

The central role played by imagination may not be contentious in the case of designing a known and traditional 'normal'[89] technology like the MHP system. However, it could be argued that the mainstay of modern engineering innovation is formal structures, especially when expert engineering scientists design a cutting-edge or 'revolutionary'[90] technology.

In order to explore if the findings are only an effect of the relatively simple technology involved in the selected empirical cases, I expanded the analysis to two comparison cases, where the engineering problems were very different from MHP:

a) the case of designing a futuristic fuel cell technology: cooling duct, gasket (Engineering Scientists: ESs)

b) the case of estimating whether the human heart can provide enough power to uncork a wine bottle (Expert Engineering Educators: EEEs)

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[89] Vincenti, *What engineers know and how they know it*, 1990, p. 210.

[90] Vincenti, *What engineers know and how they know it,* 1990, p. 210.

7.4.1 ESs’ cognitive process of design for fuel cell cooling duct

At an Indian R & D lab researching advanced fuel cell technology, a cooling duct needed to be designed, to pass cooling air uniformly through a large number of hot fuel cell plates. The engineering scientists (ESs) anticipated (i.e. imagined) lesser air flow through the plates at the end of the duct. They designed a tapering duct (in Computational Fluid Dynamics software; CFD) to avoid this, but this design created uneven air flow at both ends of the duct (when the simulation was run). (See Fig. 11, page 35). Contrary to their anticipation, more cooling occurred at the end farthest from the air inlet. (See Base case plot in Fig. 24).

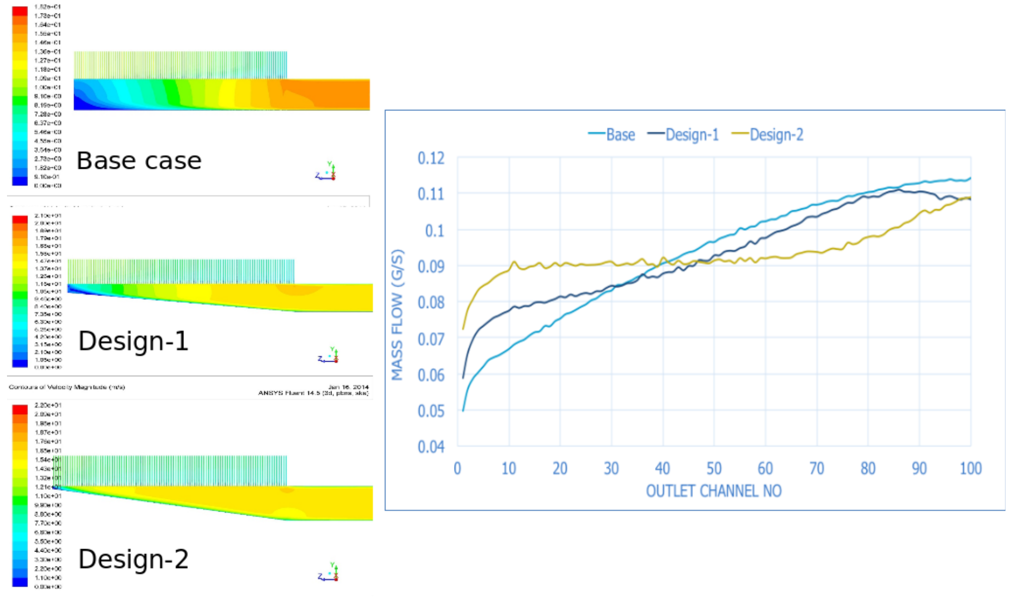

Fig. 24. CFD plots for performance of virtual cooling duct prototypes for fuel cell stack.

Imagining the air flow enabled the scientists to interpret the CFD results, and modify the design parameters to arrive at a satisfactory design. (See Fig. 25). Here the CFD simulation works as an external imagination, as without the CFD system, the 'run' of the simulation would have been done using the mind. The external CFD model also works as a 'manifested' model,[91] which helps in arriving at a consensus. The diagnosis of the problems is achieved through an understanding of the imagined

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[91] Chandrasekharan & Nersessian, “Rethinking correspondence: how the process of constructing models leads to discoveries and transfer in the bioengineering sciences,” 2018.

behavior of air, and not through formal training. CFD displayed results in the form of performance graphs, enabling the scientists to compare the performances of the various virtual prototypes with both the previous results and the theoretical standards. This allowed calibrating their design at-a-glance. The 'manifested' behavior, captured by the representations, also facilitated the team’s discussions around the design problems, findings, and decisions, and helped them communicate the final specifications to the fabricator. CFD also allowed for quick modifications of the virtual prototypes, thus saving the time and cost of fabricating and testing numerous material prototypes.

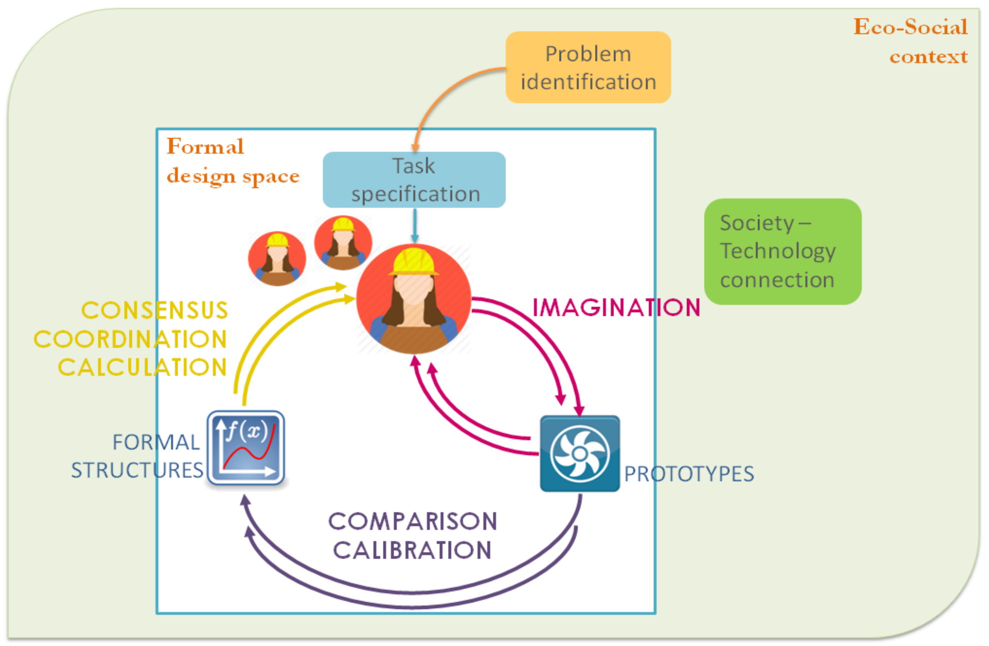

Fig. 25. ESs’ cognitive process in design of cooling duct.

7.4.2 ESs’ cognitive process of design for fuel cell gasket

At the same R & D lab, the engineering scientists were developing the technology to stack multiple fuel cell plates together, to supply more power. The scientists found that the hard fuel cell plates cracked under compression pressure, despite having a soft rubber gasket between every two plates. The team did not have any formal expertise on this problem, and could not find any obvious explanation or remedy in the formal literature.

On measuring several cracked plates, and plotting graphs, they found a pattern in the cracking – all the cracks appeared near the gaskets. Imagining their experiences of rubber behavior, they realized that the gasket may be buckling under compression pressure and slipping from its groove. So they added a wall support on the fourth side of the groove. This controlled the slippage but not the cracking of the plates. (See Fig. 26).

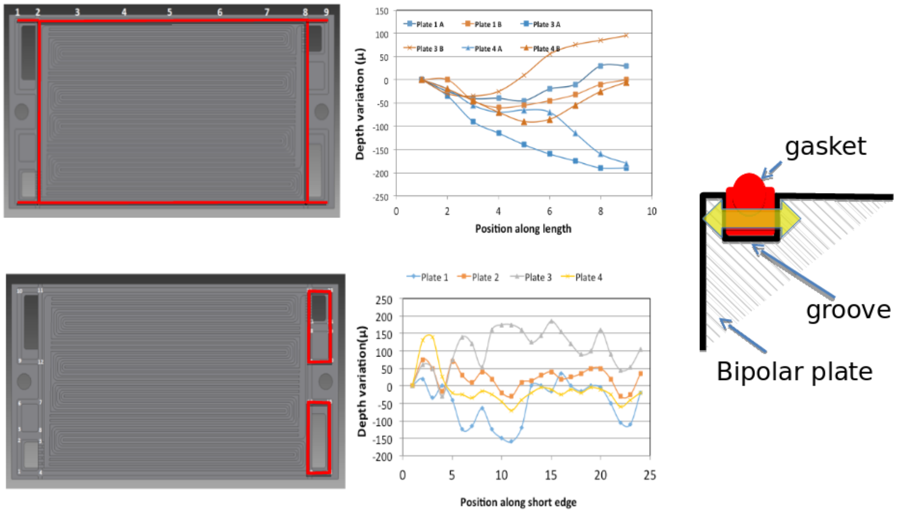

Fig. 26. Gasket plates, plots of cracking, gasket groove.

They had another hunch that the gasket was not able to expand and absorb the pressure. The hunch was confirmed by a gasket manufacturer and an expert who worked with gaskets. The gasket groove was then widened, three different groove sizes were tested, and the problem was finally solved in three months. The cognitive processes of their design can be depicted as follows. (See Fig. 27).

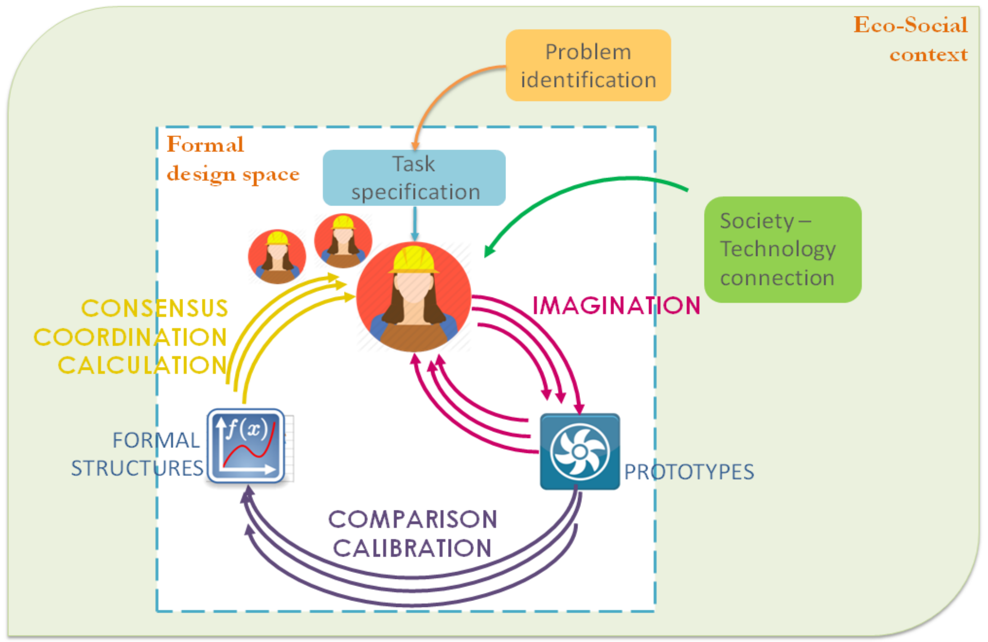

Fig. 27. ESs' cognitive process of design of the gasket groove.

The scientists used formal representations (graphs) in lieu of formal structures, to identify patterns (See Fig. 27 prototype to formal purple arrows), and discuss the gasket and plate behavior (formal to designer yellow arrows). This allowed them to imagine and arrive at a consensus about a possible solution (designer to prototype pink arrows). Despite being an advanced R&D lab, and the engineering scientists being formally trained, since formal structures were not available for this open-ended problem, the group needed to engage with others in the society, who were non-formally trained, and knowledgeable about the behavior of rubber gaskets (green arrow). They then used trial and error methods to resolve the problem. Their imagination process for this problem was thus similar to the non-trained innovator building an MHP system. However, formal structures allowed the scientists to calibrate and coordinate the prototype modifications through trial and error.

7.4.3 EEEs’ cognitive process of design

Kothiyal et al.[92] conducted a study of the process of engineering estimation, with two expert engineering educators (E1 and E2), who also had extensive practice experience. Both were independently given the problem of estimating whether the human heart could run a wine opener. According to the researchers, the experts solved the estimation problem by employing a design process that demonstrated model-based reasoning, where they first created functional models by mentally modeling the dynamics of the system based on a known system. Interestingly, one of the experts (E1) modeled the heart’s pumping function, while the other (E2) the beating function. (See Fig. 12, page 35). Each then created a qualitative model by detailing out the structure and components, based on the working of the functional model. They finally created a quantitative model by applying engineering principles, to reason, develop equations, calculate and evaluate. Both arrived at the same qualitative estimate. Only in the last phase of the estimation process, did one of them perform engineering calculations.

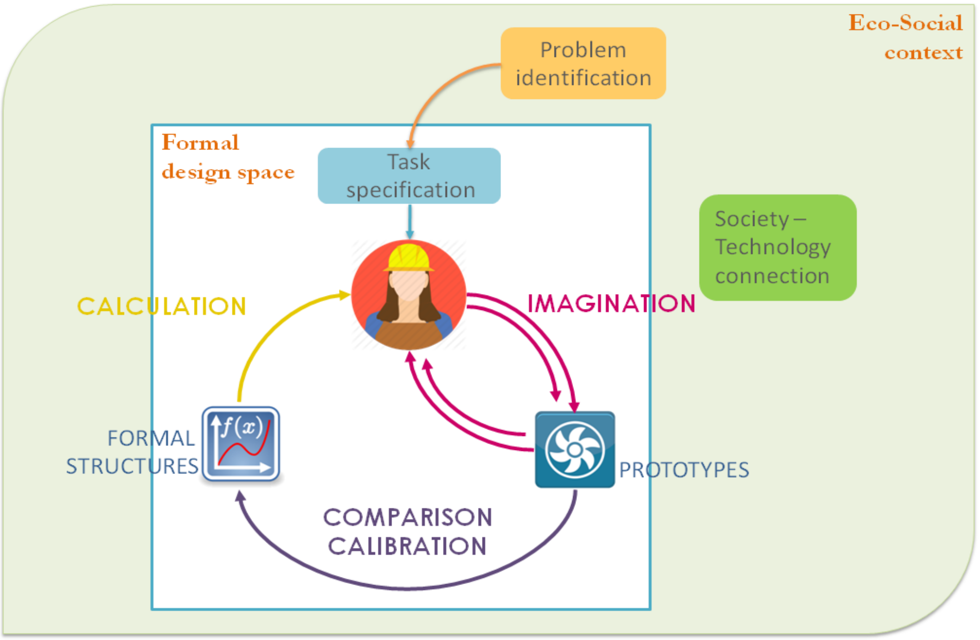

Fig. 28. EEEs' cognitive process in estimating the power of heart.

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[92] Kothiyal et al., ““Hearts Pump and Hearts Beat”: Engineering Estimation as a Form of Model-Based Reasoning,” 2016.

The experts started by mentally simulating the dynamics of the problem system (heart and unscrewing a wine bottle cork), entirely or in part. A real-world system or artifact, known to the expert, was used to 'instantiate' the simulated dynamics (e.g. heart is a pump), very similar to the process used by the GRI. The mental simulation helped them to develop an initial functional model of the situation. (See Fig. 28 pink arrows). The engineering principles helped in detailing and converging the mental simulation and model-based reasoning (See purple and yellow arrows), but the principles were themselves not generators of solutions.[93]

7.5 Comparison with the training model

These cases of practice show that even while solving a cutting-edge renewable technology problem, and in open-ended estimation problem-solving, by formally-trained experts, innovation is driven by imagination, rather than formal structures. These cases thus demonstrate that such imagination allows for a diversity of solutions, rather than one single correct answer. As a core component of the design process, imagination could thus also enable the plasticity of the socio-technical connection to enter the design process.

However, most engineering education courses do not seek to augment imagination. Instead, the use of formal structures, particularly engineering sciences and mathematics, is emphasized. Canonical engineering education thus assumes that the application of formal knowledge is the central cognitive process in engineering activity (i.e. engineering design).

7.5.1 The canonical model of cognitive processes in design training

As per this assumption, the canonical model of cognitive processes in design training would be as follows. (See Fig. 29).

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[93] Kothiyal et al., "“Hearts Pump and Hearts Beat”: Engineering Estimation as a Form of Model-Based Reasoning," 2016.

a) The designer-formal structure interaction, based on the engineer's training in formal knowledge, would be central to the design process. The interaction direction is designer to formal structure.

b) The formal structures would lead to the generation of the prototype. The interaction direction is formal structure to prototype.

c) While it is acknowledged that designer-prototype interaction occurs, the role / direction of this interaction, and the cognitive processes underlying it, would be more-or-less unimportant and thus ignored in canonical training.

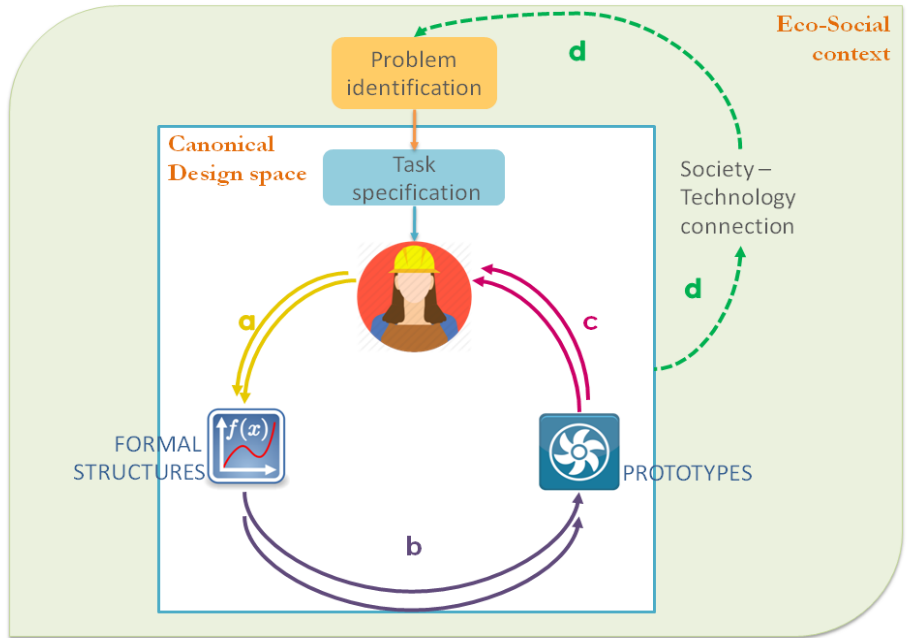

Fig. 29. Canonical model of cognitive processes in design training.

d) The formal structures within the closed design-cognition space would enable sustainable technology design, based on sustainability theory. The S-T connection and problem formulation would be external to the design space.

Given the contrasting emphasis on imagination demonstrated by the practice cases, these assumptions underlying current curricula and pedagogy need to be re-examined. One way to do this is to examine the cognitive processes in the design process of engineering students. In the next section I explore and compare engineering students' cognitive processes in the design of an MHP system for their final year engineering (capstone) project.

7.5.2 The canonical model and the cognitive processes of engineering students

Two pairs of engineering students (in consecutive batches) designed a pico hydro power system in a final-year engineering project. They calculated that annual harvest of roof-top rain water in the region, if stored, would help sustainably generate sufficient power for a household where grid-based power supply is erratic. Based on the roof height, as per theory, they decided on a Pelton-type turbine, and found its design specifications from research literature. But owing to constraints of funding, workshop facility, and time, instead of sophisticated castings, they designed an alternate Pelton wheel (See Fig. 30), with blades made of PVC pipes cut in half, and W-shaped deflectors made out of bent steel plates. (See Fig. 31).


Fig. 30. ELs' innovative form of Pelton turbine wheel.


Fig. 31. ELs' innovative splitter for Pelton blade.

Though starting with formal knowledge based on their training, when faced with a real design situation, the engineering learners demonstrated cognitive processes of design similar to the cases of practice discussed earlier. The students arrived at the actual novel material form of their turbine through imagination (See Fig. 32 pink arrows), rather than through customization or tweaking of the given theoretical parameters.

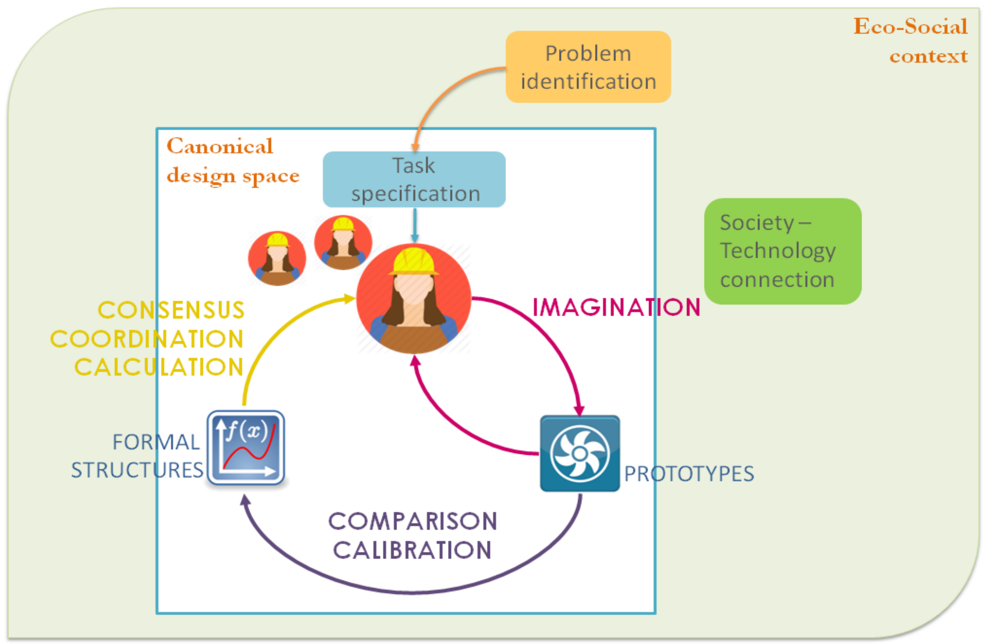

Fig. 32. Engineering Learner's cognitive processes while designing a pico hydro power system.

Formal structures helped them to compare the performance of their prototype turbine with known standards, and calibrate it (purple and yellow arrows). This also allowed them to anticipate the required specifications of the other components of their system, and communicate these to each other and to their workshop technicians. The formal structures also enabled them to arrive at a common understanding of their goals, build a consensus, and coordinate their efforts.

One of the students nevertheless strongly felt that the use of computational fluid dynamics (CFD) would have helped them arrive at a better (more efficient) design faster. This indicates that while imagination was the core cognitive process used to arrive at a prototype, its central role went unrecognized, and design innovation is attributed to formal structures (embedded in CFD).

This also shows that despite the stated goal, as well as the potential of the students' novel, low-cost Pelton turbine towards affordably solving the power problem for many, the student's primary concern was about the technical efficiency of the design. This indicates that while imagination allows for eco-social factors to enter the design process, it does not automatically ensure that this will happen. Sensitivity and training in eco-social problem formulation and SfP principles would be necessary to bring about this change in design thinking.

7.5.3 Insights from comparison with the canonical model of cognitive processes involved in training

The above comparisons lead to the following insights about the assumptions in the engineering training process, as captured by the canonical model:

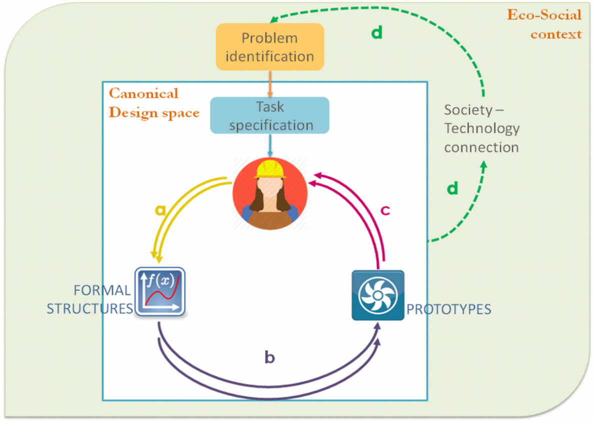

Fig. 33. Cognitive process in canonical design training. (Same as Fig. 27).

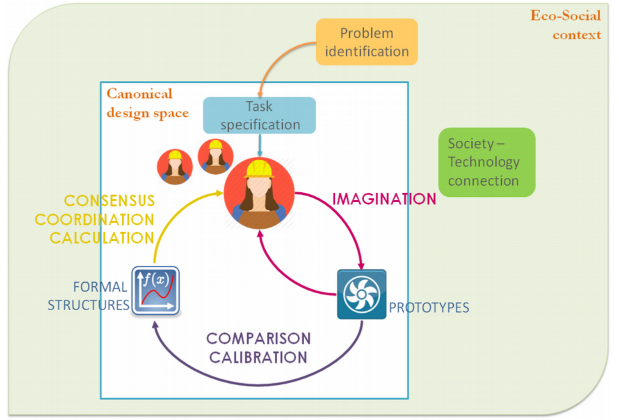

Fig. 34. Cognitive processes of engineering learners. (Same as Fig. 30).

1. Imagination, and the interaction between the engineer and the prototype (c, See Fig. 33), is central to the students’ design process. However, the canonical model assumes that formal structures are central to the design process.

2. The canonical model does not properly differentiate imagination from the interaction between the engineer and the formal structures (a, See Fig. 33), as well as the prototype and the formal structures (b, See Fig. 33), thus leading to an attribution of the work done by imagination to the processes of a and b, and a misplaced emphasis on a and b in education, neglecting imagination. This

also leads to identity formation based on a technical rationality, where the non-technical is dismissed as non-engineering.

3. The canonical model does not recognize the role of imagination in widening the design space to 1) include the eco-social, and 2) to engage with the plasticity of the society-technology connection (d, See Fig. 33). Mere formal training, without this engagement in engineering education, cannot enable students to design for sustainability.

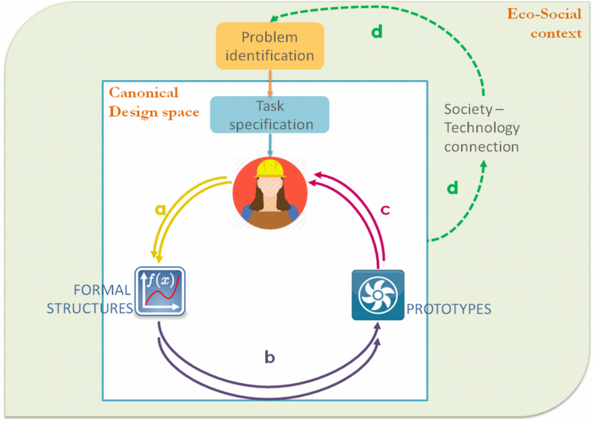

Fig. 35. Cognitive process in canonical design training.
(Same as Fig. 29 / 33).

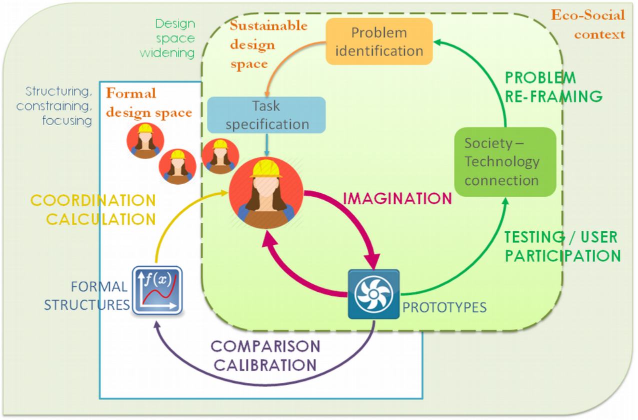

Fig. 36. Cognitive processes of engineering practitioners & learners.
(Combined Fig. 23 & 34).

4. The canonical model assumes the direction of interactions as a-b-c-a (See Fig. 35), but empirical data, from both practice as well as learning, suggests the direction is the exact opposite, i.e. c-b-a-c (See Fig. 36).

5. In mainstream industrial scenarios, the design activity is located and embedded in a closed industrial context, which forms a design space isolated from the (real-world) context of the problem. There is rarely any interaction between the eco-social context (where the problem and its solution are embedded) on the one hand and the engineer, the prototype, and the formal structures on the other. This closed structure is assumed by engineering education. Since this structure is highly sparse, and very different from the rich design space for sustainability, the current EE process need to be extended significantly to support designing for sustainability.

7.6 Findings 2 - Characterization of the cognitive processes of sustainable technology design

The key insights into the cognitive processes of sustainable design, from the analysis of the cases discussed, can be summarized as follows. (See Fig. 37).

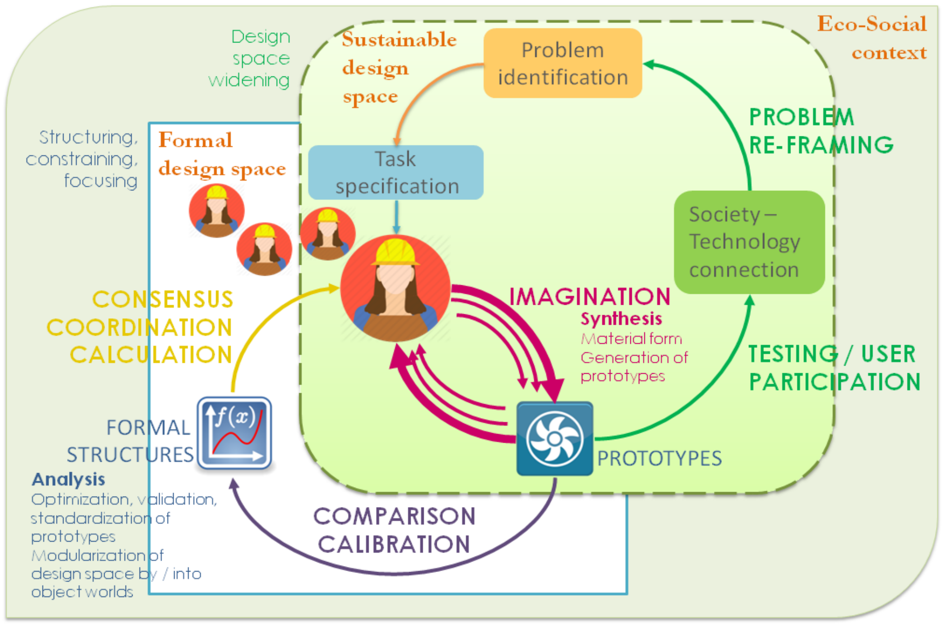

Fig. 37. Cognitive processes in sustainable technology design.

1. The Designer-Formal Structure interaction is neither primary, nor mandatory in technology design. Formal structures do not directly or necessarily lead to prototypes, or generate or synthesize new ideas.

2. Prototypes or material artifacts act both as the solutions and as external representations to think with. Prototypes are a part of the imagination process, and act as invaluable cognitive tools and strategies in the design process. As a result of this, the designers' empirical work with the materials and artifacts sometimes contributes to generation of technological knowledge in the form of thumb rules or heuristics (prototype to formal structures direction in Fig. 37).

3. Imagination allows for a widening of the design space beyond the technical input-output parameters. Generation of the actual material form (prototype) as well as the synthesis of the technical with the eco-social context happens through imagination.
4. Designer - Prototype interaction creates the space (the Sustainable design space) in the cognitive process to incorporate a variety of non-technical / eco-social / qualitative considerations.
5. Formal structures allow for comparison and coordination, help constrain and focus the search of solutions within the wide design space, and thus speed up the design process.

7.6.1 Assumptions in engineering education

This characterization provides more depth and detail to the existing critique, that engineering education overemphasizes formal structures (See Section 7.1), particularly by identifying the different cognitive components involved in engineering design, their cognitive roles, and some of the (erroneous) assumptions underlying the emphasis on formal structures. A key takeaway from this study is that engineering practice is mis-represented by engineering education, in the following terms.

Box 5: Insights about representation of practice in engineering education

Engineering practice as mis-represented by engineering education
• The work done by imagination: This goes unnoticed, unacknowledged, or gets mis-attributed to formal structures. • The design role of prototypes: The canonical model treats prototypes as instantiations of formal structures. The cases I analyze demonstrate that prototypes are products of, as well as tools for, imagination, which drives design thinking. • The cognitive role of formal structures: Formal structures play mostly a calibration and coordination role in practice, rather than a design generation role. Once a design is available, formal structures help lower the number of prototypes generated. • The way formal structures limit the design space: Formal structures constrain the imagination, by idealizing away key components of the design problem, and thus making the design un-viable in the long run. More importantly, the idealizations also make unavailable other possible design trajectories, based on

the ignored factors, and thus constrain the design space even further. The components of the formal structures may also lead to designs based on modules that map to these components, even though other modular configurations may be more viable. Finally, while formal structures lower the number of prototypes actually created, and thus speed up design, they also lower the designer's ability to learn from the prototype's behavior (as GR has done), which lowers the range of designs and their recombinations available to the designer, which help in advancing her imagination.

- Misunderstanding of design thinking: The emphasis on formal structures leads to the active roles played by imagination being ignored, or attributed to the formal structures.

7.6.2 Synthesis and analysis

In the early models of design process in literature, synthesis and analysis are discussed as two central aspects, but analysis was assumed to be the central phase. The characterization of cognitive processes in sustainable technology designs reported here demonstrates that synthesis (of the material form) is the central design process, and imagination (mental simulation) is its core cognitive process. Formal structures are cognitive tools that support the design process of analysis, through modularization of design space (into object worlds), validation, and standardization of prototypes (via comparison, calibration, calculation, and coordination).

7.6.3 Conclusion

This characterization makes it clear that the central design processes involved in design is synthesis, and not componentization, which is the key role played by formal structures. Cognitively, the synthesis role is played by imagination, which is unfortunately occluded by the emphasis on formal structures. The optimization-coordination role played by formal structures in effect also blocks designs that require wider perspectives such as sustainability. This analysis therefore indicates that the underlying assumptions of the engineering education effort are thus mis-guided, even for non-sustainable engineering designs.

This understanding, where the engineering design problem is treated as a distributed cognitive system, can help limit the emphasis on formal structures, and help engineering education move to a model where developing imagination is the central pedagogical focus. If design training is restructured, to uphold imagination as the core cognitive process of design, the design process could start from the eco-social perspective. The sustainability perspective can truly enter engineering design only when this becomes standard practice.

Chapter 8 Discussion and implications of the thesis

8.1 A brief summary of the thesis findings

This research study was driven by the question: *how can we develop a practice-based understanding of sustainability engineering, to guide pedagogy*? To address this question, I analyzed case study data from the unique Indian context of grassroots technology design – where both non-formal (grassroots innovation) and formal (non-mainstream) sustainable technology design practice co-exist – to characterize the main features of such innovation. The key outcomes of this characterization analysis are:

1. A broader design process and overarching design principles necessary for sustainability engineering (Chapter 6).
2. A descriptive model of the cognitive processes involved in sustainable technology design (Chapter 7).

The key findings can be summarized as follows.

1. The connection between society and technology is highly plastic, and recognizing this plasticity enables design innovation.

2. The socio-technical connection is plastic, but only when the design process starts from need (problem) formulation.
3. The idea of optimality goes beyond that assumed by centralized efficiency and revenue models, to include social and environmental factors.
4. Sustainable technology aims at empowering people at the grassroots and sustaining their local livelihoods, a design principle beyond drudgery / cost reduction.
5. The key cognitive process that drives engineering design is imagination (mental simulation of structure and dynamics). The synthesis of the technical and the non-technical – which is the central requirement for any engineering design – is driven entirely by imagination.

8.2 Discussion

The grassroots design cases characterized in this thesis demonstrate a wider perspective towards technology for sustainability. It emphasizes the health, well-being, and ‘flourishing together of all those interconnected’ as the goal of any intervention or solution, where the health of one cannot be improved by sacrificing the well-being of another. The ethics of such technology go beyond safety and inclusivity. They extend the ethical or moral principles such as ‘Benign by design’ and Value Sensitive Design, by moving to ‘Enabling flourishing of all’ - by design.

Borrowing from Wendell Berry, I develop this design perspective i.e. a conception of sustainability in technology design, as ‘Solving for Pattern’ (SfP). I don’t claim that this is *the* technology design perspective for sustainability, applicable across all technology design, but merely that this could be one design principle among many that are possible.

8.2.1 Solving for Pattern as an overarching perspective / framework supporting sustainable technology design

In generic terms, the SfP approach to building – be it engineering design of products and systems, or a broader sense of technology-based practice such as farming – primarily visualizes technology as embedded in a web of interrelationships connecting society and ecology, rather than technology being isolated and independent. Building always alters eco-social relationships. Hence, SfP requires designing technology in full consciousness and sensitivity of this fact. Many of these relationships may not be readily obvious or apparent, but the process of building technology, if it is to sustain the biosphere and the human species, needs to be extremely mindful of this web of life. Thus embedded, technology could be conceived to form and support positive or contributive relationships with the larger eco-social systems, rather than creating destructive, or merely neutral, relationships. The larger patterns of nature itself are expected to be the model for devising such relationships. Unlike most bio-mimicry based designs, this imitation of nature's relationships is for the thriving of all, not just human beings.

8.2.2 Solving for Pattern and technology at large scale

Is the SfP perspective only applicable to the limited sphere of small-scale, local technology design? It may not be possible to answer this question systematically without exploring many more cases of technology design, small and big. But it may be possible to address it to some extent, based on the current cases, which lead to a counter question, as to whether large-scale / quantity is really required, and required in the current centralized manner. If not, then decentralized units may be installed in as many places as necessary, to meet demand. Moreover, a family/community scale technology could be easily replicated or used sustainably in multiple sites. To illustrate this, three large-scale examples that could walk a path towards SfP could be cited:

1) Organic farming in a solar power plant, at the Cochin International Airport Limited (CIAL), Kochi, India: Solar panels installed over 45 acres supplied power to the entire airport. Vegetables were cultivated between the panel rows over three acres. Water used to wash the panels irrigated the vegetable patches, which also kept the dust on the panels to a minimum. This maintained the technical efficiency of the panels, provided gainful employment to people who live near the airport, and more utilization of the vast track of land and the sunlight it receives. Organic vegetables are available to the community and travelers.

2) Reversing desertification through a desalination plant, at the Sahara Forest Project, Jordan: Initiated with Norwegian support, the project attempts to utilize seawater, concentrated solar power (CSP), and atmospheric CO2, to produce food and other biomass, fresh water, as well as energy in the desert. The project supports re-vegetation of the surrounding land, thus restricting and reversing the process of desertification. The vegetation in turn reduces dust, and keeps the CSP mirrors clean. Cultivation of fast-growing biomass such as fish and algae in the salt water ponds, by harvesting the sun and sequestering CO2, also creates many skilled and unskilled jobs for local people. The project is based on the understanding that environmental problems are interlinked, and therefore their solutions must also be designed in a systemic manner.

3) Reversing migration through integrated agri-horti-forestry plantation BAIF’s Wadi Project, India: An integrated agri-horti-forestry plantation project, where a small plot of land (an acre) owned by a tribal family is brought under cultivation. Apart from sixty fruit trees of cashew, mango, gooseberry, the plot is cultivated with fodder and timber trees on the boundary, and intermediate crops and flower trees in the spaces in between. In five years, the family’s fallow land is converted into income-generating assets. Entirely organically grown fruits and other produce is further value-

added and marketed through a larger federation of such units. This model provides short-term as well as long-term gainful self-employment, and has been widely implemented across India.

While these cases illustrate scale to some extent, a limitation of SfP could be that it may not be possible to apply the underlying principles of eco-social optimality and decentralization to large scale industries. For example, those based on mining of centralized resources such as oil and ores.

8.3 Policy recommendations based on the findings

Based on the studies and the analyses, I develop two policy recommendations to redesign engineering education for sustainability - a) engineering design instruction needs to change, to ‘solve for pattern’, starting with eco-social problem formulation, and b) engineering selection and training needs to be based on developing imagination and synthesis skills.

Following recent trends,[94] introducing sustainability engineering at the secondary and higher secondary school (K-12) level is also recommended.

Given the short time-window available to move to sustainability, and the inertia generated by existing structures, reforming the current EE framework and institutions may not be the most productive approach in moving towards implementing these recommendations. For faster implementation, new interdisciplinary institutes that bring together ecology, engineering, design, and humanities, need to be created, to research and promote sustainability engineering.

8.3 Implications of the thesis

The following section discusses the wider implications of the findings, particularly for research, engineering practice, and pedagogy.

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[94] Linda Katehi, “Committee on K-12 engineering education,” 2009, cf CHEER, 2014.

8.3.1 Theoretical implications

8.3.1.1 The perspective of Solving for Pattern (SfP)

Solving for Pattern, as an eco-social approach to technology design, helps analyze how the human building instinct – the biological motive underlying engineering practice – has deviated from its biological function over time, and has moved into a runaway mode.

For instance, the biological principle of form following function allows us to consider the practice of building – engineering or designing any technology – as manifesting its design values (such as efficiency) in the technology it creates. Once manifest, the technology, and the values it externalizes, becomes part of society. This manifestation allows the values of design and practice to permeate social narratives, eventually leading to an overall cultural narrative (such as the 'more-for-less' narrative) based on these values. This cultural narrative then loops back, and reinforces the values underlying the designs. Over many cycles, this cycle creates a positive feedback loop that both reifies and expands the existing technology design model (See Fig. 38), which is currently one that significantly damages ecological and social structures that are benign.

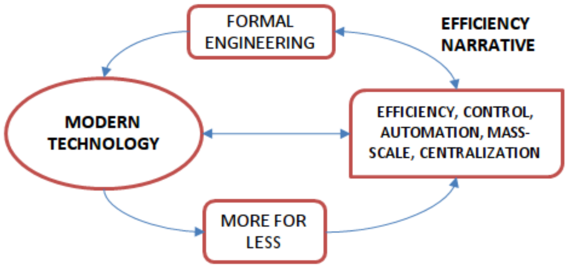

Fig. 38. The modern formal engineering practice where efficiency is a key value.

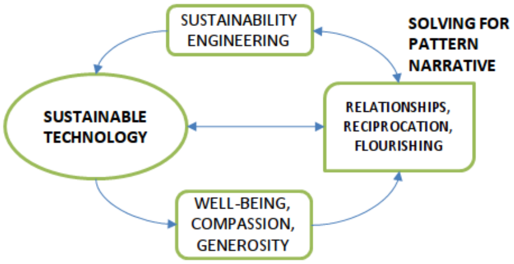

Fig. 39. The SfP building practice is founded on sustainability values.

The reinforcing feedback loop based on this, and related values, have now created the runaway practice of constantly building technology, leading to ecological and social damage at a corresponding global scale, and a very unsustainable way of life on a finite planet.

The SfP approach provides one way to visualize a systemic change – a way to alter building practice, technology, and values to support flourishing. (See Fig. 39). Building always alters eco-social relationships, to create favorable or adverse impacts on these patterns. Rather than the hidden / implicit hubris of techno-scientific rationality, SfP urges a building process that is explorative, sensitive, and benevolent, ensuring that the interrelationships are least disrupted, if not actively strengthened.

Moving from purely efficiency narratives towards SfP may not be an instantaneous transition, and Systems Engineering and Industrial Ecology may be intermediate stages. For example, a design thinking approach may start from these, and transition towards SfP to solve many environmental problems (such as groundwater pollution), which are created by the coming together of many misguided building projects (such as garbage dumps and untreated effluents), and thus requires designs that bring together many engineering and social components (such a bio-remediation based on farming plants such as Vetiver). Fig. 40 captures the expanding narratives and SfP as a wider approach.

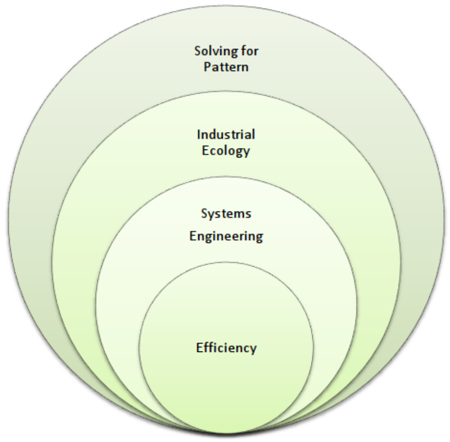

Fig. 40. From efficiency narratives towards SfP.

SfP could thus reshape the very meaning and goals of technology, design, and building, beyond the limited contemporary definitions, and thus help define sustainability engineering in a new way at the operational level. This design principle provides the hope that technology, in its broadest sense, could be designed differently, and the building instinct reshaped, to enable a sustainable way of life for the entire biosphere.

Moreover, SfP can enable a new practice perspective and approach in wider applications, beyond engineering-specific product building, to technology understood as activity, knowledge, or even volition.[95] It is relevant for every sphere of life, because the runaway building values have percolated into the cultural narrative, to the extent that all kinds of systems, such as food, healthcare, and education, are now driven by the same unsustainable values.

8.3.1.2 The cognitive processes of technology design

The analysis of the cognitive process of design I present is loosely based on the distributed cognition (DC) framework, as it examines how cognitive processing is spread across internal operations, external representations, artifacts, and people, and how this distributed system helps achieve both innovation and coordination. This approach presents a novel way to examine design cognition, and offers possible approaches to develop mechanism models of design thinking, similar to recent work proposing cognitive/neural mechanisms that support DC.[96]

The prominent approach to understanding design cognition has been information-processing theory. Field theories of cognition, such as distributed, situated, and embodied cognition, have not been used much to analyze design cognition. The analysis presented here provides a good starting point to develop such a theoretical approach, especially to understand the role of model-based reasoning in engineering design.[97]

The run-time use of the environment for cognition, such as using prototypes for thinking, is a key focus in the study of situated cognition. Design by non-formal practitioners would thus be a good domain to study situated cognition, especially how the environment is changed to advance cognition. This approach could help advance our understanding of tacit knowledge and situated cognition.

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[95] Mitcham, *Thinking through technology: The path between engineering and philosophy*, 1994.

[96] Rahaman et al., “Recombinant enaction: Manipulatives generate new procedures in the imagination, by extending and recombining action spaces,” 2018; Chandrasekharan & Nersessian, “Building Cognition: the Construction of Computational Representations for Scientific Discovery,” 2015, Chandrasekharan, “Becoming Knowledge: Cognitive and Neural Mechanisms that Support Scientific Intuition,” 2014.

[97] Kothiyal et al., ““Hearts Pump and Hearts Beat”: Engineering Estimation as a Form of Model-Based Reasoning,” 2016.

The model of cognitive processes in design I propose is based on an analysis of formal, non-formal, and student cognitive processes in design. This analysis thus provides a framework to bring together design by novices and design by experts, and a way to understand the systematic development of design cognition, and of how formal structures expand/constrain design thinking.

8.3.2 Implications for the practice of engineering design, and building in general

The SfP approach to technology development makes it possible for technical values (such as efficiency and optimization) to be subsidiary to the larger sustainability values of well-being, interrelationship, and flourishing of all. More broadly, this allows for sustainability to be understood and addressed as the central problem of engineering practice.

8.3.2.1 Design innovation through plasticity of socio-technical connections

Currently, engineering practice is incarnated (/concretized/embodied) in close connection to the current technology-business/commerce structures (activity of buying and selling). A restructuring of the current model is already under way, with software technology models such as Kickstarter, Kiva, and online marketplaces. Free and Open Source Technologies and creative commons are good examples from the software domain that demonstrate and contribute to a more just and fair technology development and use. They promote global values that can be adopted locally. AM's case demonstrates the empowerment potential of such disruptive models, especially in the case of engineering for health and hygiene products such as sanitary napkins. Similar disruption, through a restructuring of the contemporary centralized mass production model, would be an effective way to reorient current engineering practice towards sustainability.

Problem formulation as a necessary first step of technology design – instead of starting with conceptual design – will allow the mainstream practice to reform its canonical design process for plasticity and innovation. The processes of need identification, problem definition, scoping and framing will bring in sustainability values in a wider sense, compared to their narrow interpretation as technical concepts. Such a change also requires recognizing and supporting new engineering profiles or identities, such as social entrepreneur, development consultant, grassroots innovator or designer, which value creative and participatory processes.

Designing technology ‘for supporting sustainable livelihoods’ would be one way to refocus practice from perpetuating the values detrimental to sustainability, such as consumption and abundance, which are based on designing technology ‘for luxury/comfort/convenience/drudgery reduction’.

8.3.2.2 Solving for eco-social needs as a new approach to engineering science research

‘Paperfuge’[98] - a low-cost hand-operated centrifugal machine for testing blood, addresses the problem of limited electricity access in medical labs in Africa. The design 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. This example shows that engineering sciences could also benefit from such a widening of the design space, by engaging with eco-social needs.

8.3.3 Implications for the education of engineering and design, and educational policy

Current engineering education has accepted the narrow optimality-profit combo as the only design value and norm. This combo generates a hidden curriculum, where ‘more-for-less’ is the central value, which blinds engineering students to wider design possibilities, especially for sustainability. This underlying structure makes reforms to existing curricula / pedagogy segmented and peripheral.

8.3.3.1 Training to design for enabling sustainable livelihoods

An engineering program that integrates courses, project work, and internships based on the approach of Solving for Pattern could provide training to address sustainability problems effectively.

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[98] Bhamla et al., “Hand-powered ultralow-cost paper centrifuge,” 2017.

Training for designing technology that enables sustainable livelihoods could be one such course. Such a course could make ‘learning by doing’ a necessary pedagogical component for all stages of the design process, including need identification and problem formulations. It would also discuss contrast cases that highlight how a failure to sensitively handle the interconnectedness and eco-social relationships leads to sub-optimal technology designs. Special credits could be allocated to encourage non-mainstream grassroots projects and internships.

Designing technology for sustainable livelihoods could also emerge as a possible model for other sustainability engineering programs, where the knowledge-skills-values transacted would be integratively built into the pedagogical design, rather than be segmented.

8.3.3.2 Nurturing imagination and eco-social values

The competencies required for sustainability engineering are still not well-understood and agreed upon in the engineering education community.[99] The design practice I have characterized suggests problem formulation capabilities (especially for an eco-social context), imagination, as well as synthesizing capabilities, as the core competencies that support sustainability engineering. Students need to learn (to use) the formal structures, but also be able to develop and practice fluently other cognitive alternatives distributed across real-world structures, and situated in the eco-social context. Case studies, which are widely recognized as an effective pedagogical tool to support this type of reasoning, would thus be the ideal way to train for sustainability design, as they also help develop tacit knowledge and help situate students in authentic contexts.[100]

Given the current mutually reinforcing and circular system, where selection, training and assessment is for formal structures and analysis skills, it is very difficult to build in sustainability

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[99] Segalas et al., “What has to be learnt for sustainability? A comparison of bachelor engineering education competences at three European universities,” 2009.

[100] Heymann, “Engineering as a Socio-technical Process: Case-Based Learning from the Example of Wind Technology Development,” 2015, Jonassen, “Engineers as problem solvers,” 2014.

values and practices. One way to reform this system would be to revise the entrance or qualifying examinations, such that they also screen for imagination, as well as the sensitivities valuable for sustainability engineering.

8.3.3.3 Grooming for a wider engineering identity

In the current education system, students' engineering identity gets constituted only through their educational training and competence with formal structures. Gary Downey[101] has raised the crucial question of whether the entire challenge of training engineers is really about imagining and grooming the right engineering identity. The cases discussed in this study outline a spectrum of role models, which bring forth a diversity of possible identities in the practice of engineering design for sustainability. 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, where collaborations between trained designers, experienced craftspeople, and lay users, lead to innovative sustainable technology. The case of Danish wind technology illustrates the possibilities of such collaborations, and it is already part of Aarhus University (philosophy of engineering) curricula for undergraduate engineering students.[102] Case studies such as DWT, AM, GR, and EP, when integrated with the respective modules in engineering curricula, could support the development of an alternate engineering identity, and build among students the sensitivity necessary for understanding the larger patterns. The key difference from the current sustainability curricula would the focus of these cases on 'flourishing together of all', which is broader than the current anthropocentric approach to design.

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

[102] Heymann, "Engineering as a Socio-technical Process: Case-Based Learning from the Example of Wind Technology Development," 2015.

8.3.3.4 Implications for science education

Support and recognition could be provided to these innovators through science textbooks and curricula. The technology design efforts of grassroots innovators could be included to showcase the value of generating techno-scientific knowledge outside sophisticated laboratories, and the value of learning by doing. Their stories would not only bring respect to the innovators, but also provide role models to science students, to engage with the societal problems around them, and to persist in solving such problems using their knowledge and skills in formal and non-formal science and technology.

Further, in environmental education curricula, the discussion around sustainability would be enriched by an understanding of design considerations and concerns of doing technology, and their implications. For students, understanding the nature of technology, and what kind of technology we want to do, is as important as understanding what kind of science we want to do, for sustainability.

Adopting broader approaches, such as SfP, towards sustainability engineering right from the K-12 stages could help avoid many of the pitfalls of the current engineering and science education. It may also be productive in Design & Technology education to draw upon real-world contexts, particularly the needs of technology for sustainable livelihood.

8.3.4 Implications for research and methodology

This study demonstrates that the multiple case study method could be used in design studies of practice ‘in the wild’, when ethnography may be limited in the case of historic episodes, while protocol studies would limit the study of practice to controlled conditions in labs. The cross analysis of multiple cases, as illustrated in this work, can be one way to look for converging generic principles, even when using the qualitative case study method. Further, combining the practice lens (thematic analysis with design episodes and transitions) and the cognitive lens (cognitive-historical analysis with designed artifacts) would be powerful while analyzing the interrelationships between design practice and thinking, across time.

Moreover, data from simulations and similar virtual design spaces could be used to more deeply probe both the practice and cognitive aspects. The simulation tool we developed provides a quasi-experimental structure, where clear situations could be set up and tested with different participants, either as a probe for design thinking, or for training.

8.4 Contributions and limitations

8.4.1 Contributions of this thesis project

This thesis is the first systematic research project to:

- Develop an evidence-based operation-level approach to designing curricula and pedagogy for sustainability engineering.
- Characterize the formal and non-formal situated practice of grassroots technology design.
- Study technology design practice in the unexplored domain of non-formal design (particularly, grassroots innovators).
- Characterize the cognitive process of sustainable technology design across formal and non-formal engineering innovators.
- Analyze the nature of non-formal design thinking in the light of distributed and situated cognition (rather than the classical information-processing model).
- Bring together studies from three distinct viewpoint levels – of practice (macro-level), design process (mini-level), and design thinking (micro-level), from across a wide range of scholarly disciplines that study engineering and technology – to develop an understanding of the nature of engineering, as well as the foundational assumptions underlying engineering education.

- Bring to light the implicit aspects of mainstream engineering, and its practice and identity defaults, against the contrasting cases of non-formal technology design.
- Probe technology design thinking using a novel context-situated simulation tool developed specifically for this purpose.

8.4.2 Limitations of this thesis project

- The key empirical cases of design practice were historical, so the primary data was not in real time. This required participants to depend on memory. This limitation was somewhat offset using the simulation studies.
- No cases of grassroots women technology designers were studied, as these were not readily available. The conclusions could change for such cases.
- The simulation tool, while helpful in recreating the basic design situation, set up a well-defined problem, and provided limited feedback. These factors could have affected the responses of the designers.
- Student data was collected only as a contrast case. It confirmed the understanding from literature. For this reason, it was not analyzed in greater detail. It is also not reported here in detail.
- The analysis identifies the limitations of the canonical design process model. However, at the current stage of the work, I do not present an alternative / replacement model.

8.5 Future work

There are many ways to take this work forward, the following are some of the ways that are being pursued.

- The study of grassroots innovators to understand their problem formulation further, in order to learn to design technology for sustainable livelihoods.
- The design of pedagogical interventions to train students in eco-socio-technical problem formulation, particularly a theme-based, rich, model case study module.
- Integration of case studies and assessments as part of technical modules, to expand student understanding and values.
- Developing a traveling workshop for engineering colleges.
- Designing a model internship in grassroots design.
- Extending the basic simulation to advanced level, for probing as well as learning.

Conclusion

> *"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".*[103]

It is now not far-fetched to extend Langdon Winner's above warning about 'building order' to the 'building instinct' itself, since the very survival of the human race and sustenance of life on Earth now balances precariously on how we reshape our building instinct, and in turn the technologies we build. This thesis project hopes to have contributed one step in this direction.

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

Publications based on this thesis

Journal papers

1. Date, G., & Chandrasekharan, S. (2018). Beyond Efficiency: Engineering for Sustainability Requires Solving for Pattern. *Engineering Studies*, 1-26. DOI:10.1080/19378629.2017.1410160

2. Dutta, D., Date, G., & Chandrasekharan, S. (under second review). Solving for pattern: a model of technology beyond efficiency. Submitted to *Journal of Environmental Values*.

Refereed conference papers

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