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Abstract

The paper aims to build understanding of the recent growth of interest in engineering for international development as an emerging focus of new knowledge, practice, and community development. In the paper, we create a borderlands approach to studying the activities referred to as engineering for development and development engineering. These activities take place in "borderland" spaces where new approaches are being tried out through creative engagement of networks and communities willing to integrate social as well as technical knowledge and practice. We analyze four cases, selected as exemplars of engineering for development, from a large data set of case studies to demonstrate the socio-economic impact of research. We found evidence of important and original engineering, which showed paradigmatic shifts in engineering knowledge and practice. There was ambivalence inside the engineering community about engineering quality, mixing pride in the building of new paradigms with modesty about whether new knowledge and practices were "real" engineering. These findings provide evidence that engineering aimed at global development offers an exciting new "borderlands" approach to engineering that warrants further study.

Keywords: Engineering and development; borderlands; engineering knowledge; practices; communities

Introduction

Both the practice and study of engineering for development (E4D) and development engineering have grown significantly since 2000.[1] This paper aims to build better understanding of this growth. We will argue that E4D can be thought of as a borderland activity and that this is manifested in three interconnected domains: *knowledge*, the

[1] Nieusma and Riley, "Designs on Development."

emergence of new and changed forms of engineering knowledge; *practices*, meaning both artifacts and also types of engineering work; and, knowledge *networks and communities* of practice, that is new groups of practitioners who work together, to common purpose.

Development engineering is about making things and building systems that provide solutions to global problems with a focus on those people normally left out of the development process. Terms such as humanitarian engineering, inclusive and frugal innovation, and appropriate technology are often associated with development engineering. The term engineering for development encapsulates varieties of engineering knowledge and practice that are explicitly used to provide solutions to global problems. This includes, but is not restricted to, engineering associated with health, shelter, water, transport, agro-food, energy and communications. It thus refers more broadly to those engineering activities, however and wherever generated, that are useful in an international development context.[2] Because our concern in this paper is engineering broadly within international development, we normally use the term E4D.

Our main argument in this paper is that E4D work is not as marginal to engineering as it is often portrayed. Rather, it is an emerging focus of new knowledge, practice and community development. We use the ethno-geographical term "borderlands" to help conceptualize this hybrid space. Just as E4D has become less marginal to engineering, the recent study of borderlands has moved the focus of several fields from the study of marginal spaces towards "the centrality of the margins."[3] Studies of borderlands investigate how different societies rub up against each other. Brunet-Jailly suggests that borderlands are frontier spaces with "territorial markers and functional-fluid vectors of demarcation," that are also evolving and transformational.[4] Donnan and Wilson suggest that borderlands are not only the locus of forces and institutions that threaten sovereignty, but are also the focus of wider forces of social, economic, political and cultural transformation. They report on an "explosion of ethnographic work in borderlands" that focuses on those who live, work and cross borders.[5] Anthropologists have studied borders as points of connectivity: "Anthropologists approach these borderlands more as countless points of interaction, or myriad places of divergence and convergence at and around the borderline."[6] Sociologists

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[2] Robbins et al., "Development Engineering Meets."

[3] Nugent, *Boundaries, Communities and State-Making in West Africa*, iii.

[4] Brunet-Jailly, "Special Section: Borderlands," 1.

[5] Donnan and Wilson, "Borderlands," 4.

[6] Donnan and Wilson, "Borderlands," 3.

and historians have also developed theories of borderlands, predominantly but not exclusively from empirical studies of the United States Southwest. [7]

Beyond a generic approach to borderlands as transformational spaces, some use the concept of borderland to go beyond territorial space to include spaces of knowledge and practice. The longstanding organizational behavior literature on boundary spanning is one place where borderlands has proven useful.[8] For another, James uses borderlands to understand the fuzzy nature of what she calls the "medical domain," specifically the knowledge and practice of psychiatry among migrants and refugees.[9]

The study of "borderlands" has gone beyond frontiers and barriers between people to focus on permeable spaces of interaction that bring together populations, ideas, materials and activities.[10] We suggest that, as a borderland space, E4D is a particular type of meeting space where exciting new approaches are being born from the blending and fusion of diverse ideas and communities.[11] This extemporization of E4D as borderland maps onto the three domains in which we argue that it manifests itself: it has spaces for new knowledge creation; exhibits hybrid forms of work and practice;[12] and is populated by mixed communities and networks.[13]

Here we suggest the need to understand the centrality of borderlands to analyze the role of engineering in cross-cultural development contexts. The borderlands in question are those spaces where engineering knowledge practices and communities are less narrowly technical and more aligned with human development needs. Technical knowledge is required but so is a range of other forms of knowledge. Borderland work implies the shaping of new pathways of innovation, and thus new routines. E4D, we believe, is at an early, but unmistakeable, stage of growth of something significant that will change thinking about engineering's relationship to the world. Such work will become, we argue, less marginal and more mainstream over time.

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[7] See, for example, a burgeoning historical literature: Weber, *The Spanish Frontier in North America*; Weber and Rausch, *Where Cultures Meet*; Hamalainen and Truett, "On Borderlands;" Nugent, *Boundaries*.

[8] Aldrich and Herker, "Boundary Spanning Roles;" Williams, *Collaboration in Public Policy*.

[9] James, "Borderlands," 22.

[10] Hendricks, *The Wind Doesn't Need a Passport*.

[11] See Manzana and Benito, *Cities, Borders and Spaces*, for more explanation.

[12] Boundary work is well analyzed by Gieryn, "Boundary Work," and *Cultural Boundaries*.

[13] Boundary organizations are analyzed by Guston, *Between Politics and Science*.

What makes E4D special so that it can be presented as a template for those striving to build new practices in engineering? The study of engineering as applied to international development is important not only within the study of development specifically, but also because it allows insights into the nature of engineering in general. Trevelyan, in his study of engineering, showed that engineering needs to be understood as a much broader human social activity than just design and technical problem solving.[14] He went on to show that engineers tend to relegate social aspects of their work to a peripheral status and to argue that engineering practice is "distributed expertise enacted through social interactions between people."[15] Much E4D crosses boundaries of engineering, often displaying a wide breadth of engineering knowledge across various sub-strands of engineering. Furthermore, the international reach of research and practice is very extensive, covering a huge number of countries and all regions of the world.

The classic, and well-critiqued, notion of engineering knowledge as solely knowledge that applies science has largely been discarded; it is now widely accepted that engineering is an "autonomous body of knowledge, identifiably different from the scientific knowledge with which it interacts."[16] Vincenti defined engineering as the practice of organizing the design, construction, and operation of an artifice that transforms the physical world around us to meet some recognized need. As part of his research on design engineering, Vincenti used Constant's concept of "normal" technology as "the improvement of accepted tradition or its application under new or more stringent conditions."[17] We suggest that E4D, as a borderlands activity, involves a diverse set of knowledge and practices, which together amount to a form of post-normal engineering.

Our argument is based on analysis of a large database of 150 case studies, the aim of which is to demonstrate the socio-economic impact of engineering research. We found that much of this research and its impact was both "excellent" in the "normal" sense of evaluation of what is high quality "best engineering" and also "appropriate," in the sense of addressing issues of global inequality and social justice, which often requires new and diverse, complex practices.[18] Normal engineering here is used in the sense of engineering that is regular work

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[14] Trevelyan,"Reconstructing Engineering from Practice."

[15] Trevelyan, "Reconstructing," 1.

[16] Vincenti, *What Engineers Know and How They Know It*, 3-4

[17] Vincenti, *What Engineers Know and How They Know It*, 7, referring to Constant, *The Origin of the Turbojet Revolution*.

[18] Nieusma and Riley, "Designs."

within a settled paradigm of engineering theory and practice;[19] while "best" engineering may be characterised as:[20]

- science and theory based, and less related to best practice, which of necessity can change with development context;
- discipline oriented and thus not relevant to complex development problems that require multidisciplinary and interdisciplinary solutions; and
- technically quantum-leap rather than gradual, incremental improvements or new ways of keeping things going.

In contrast, the new borderland knowledge we find can be termed "post-normal" in the sense of knowledge where there is systemic uncertainty and where traditional methodologies are ineffective.[21] Michelfelder suggests that such engineering should be framed as post-normal in that it is focused on complex systems, the acceptance of negotiated risk, an increased willingness to involve a wide range of publics and stakeholders in design, and the emergence of "new ways of configuring the professional domain of engineering itself, with a progressive erasure of traditional academic disciplines."[22] Verrax asks how engineers might respond to such novel ways of dealing with knowledge in the form of data and information.[23] Such a transformation would change practices and the communities of practice and networks involved in engineering work. Such practices are likely to involve communities and networks that are complex in the diversity of their expertise, skill, and interest. Communities of practice are groups of people that share a concern or passion for something they do and learn to do it better as they interact regularly. Wenger introduces three dimensions: mutual engagement, a joint enterprise, and a shared repertoire of ways of doing things. Communities of practice are shared domains with commitment to the community, a shared identity around a knowledge domain, and sustained learning around it.[24] Networks cover a broader range of informal, emergent relations, interactions, and connections: formally, nodes and lines where nodes are individuals, organizations, and institutions and lines denote social interactions. Thus, a network of innovation could include those with ideas and artifacts, and those who interact to make the idea or artifact part of "normal" practice. All communities of practice are

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[19] Kuhn, *The Structure of Scientific Revolutions*.

[20] Robbins et al., "Development Engineering."

[21] Funtowicz and Ravetz, "Science for the Post-Normal Age."

[22] Report by Verrax, "Engineering Ethics and Post-Normal Science," 78, on a talk given by Diane Michelfelder at the Forum on Philosophy, Engineering and Technology in 2016.

[23] Verrax, "Engineering Ethics."

[24] Wenger, *Communities of Practice: Learning, Meaning and Identity*.

networks but most networks are not communities of practice. Such communities are transformational borderland spaces.

Method

The present research began when, even in a period when science innovation and development had become more visible, we became aware that engineering had become relatively invisible in development studies. As an example of the invisibility of engineering, of the 20 "top" international development impactful case studies from the UK research evaluation exercise (REF 2014) as selected by the United Kingdom Collaborative for Development Sciences (made up of all the UK's government research funding agencies together with major charities like the Wellcome Trust), only two were from engineering.[25]

We began the research by searching through all 6,622 socio-economic impact case studies from the 2014 research evaluation exercise of UK universities, called the Research Excellence Framework (REF). From this total, by using a six-category selection template, we selected all 124 case studies that could be broadly classified as engineering for development.[26]

Our preliminary analysis revealed a range of outcomes.[27] We found evidence of paradigmatic shifts in engineering knowledge and engineering practice, and of new pathways of innovation. We found that much of this type of engineering was strongly interdisciplinary, with strong elements of ecological modernization in that it sought environmental/social gains while being financially sustainable. Both interdisciplinary and ecological modernization approaches involve diverse knowledge and acceptance of new practices, requiring networks for their realization. Our preliminary analysis also found that although there were not many "development engineers" in any one organization, taken together they added up to be a strong and diverse mass of knowledge and practice expertise.[28]

We looked for ways of describing E4D practices that went beyond the normal. We felt that solving the really hard issues of poverty and inequality might bring up new practices and original ways of using established practices. We were influenced by the findings of

[25] UKCDS, "The Global Impact of UK Research."

[26] Robbins et al, "Mapping Engineering."

[27] Robbins et al, "Mapping."

[28] Development engineer is a term used to describe those engineers who work on international development related activities.

classic literature on organizational learning and learning from practice – that network, partnership, and team engagement would bring new knowledge and practice.[29]

From this preliminary analysis, we concluded that a more detailed case study analysis would yield insights on E4D as borderland activity. We selected four case studies for more detailed analysis using a framework based on knowledge, practices, and communities as outlined earlier. Our selection criterion was to choose cases that: first, illustrated engineering both as a high-quality activity requiring leading edge expertise, and also as a useful and appropriate activity for improving lives in developing countries; and second, cases with sectoral and geographical practice diversity. The cases were analyzed using a range of questions, including: what is the engineering excellence? What kinds of engineering knowledge are being produced? Who are the key users/stakeholders in developing new practices? What networks of innovation, and what communities of engineering practice are created? What kind of value model is developed: is it primarily economic, primarily social, or mixed? We analyzed a wide range of secondary resources published on each case, little of it published in peer reviewed outlets, most being in the form of "gray" literature from evaluation reports and similar funder reports. We used published summary reports prepared for the UK REF exercise 2014.[30] We also conducted in-depth semi-structured interviews with the lead investigators or their nominees. In most cases there were multiple interviewees from the case study research teams.

We transcribed all interviews and began our analysis using a preliminary framework developed from earlier work.[31] That earlier work established that many REF impact case studies with an engineering orientation used an ecological modernization storyline to build a case for the excellence of their E4D, framed as combining economic value, efficiency, and environmental stewardship.[32] Our approach was adopted to get beyond the normal "best" versus "appropriate" dichotomy, where engineering for development outcomes (products, processes, services) are typologized as either excellent "best" engineering or "appropriate" for pro-poor populations and therefore often perceived as somehow second class. We wanted to see successful engineering that went beyond that dichotomy. Beyond that, and in line with our focus on knowledge, we were interested in additions to engineering knowledge generally and how they could be described from our engineering and development case studies.

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[29] See Argyris and Schon, *Organizational Learning*; Schon, *Reflective Practitioner*; Senge, *The Fifth Discipline*; Wenger, *Communities of Practice*.

[30] Impact case studies are published as https://results.ref.ac.uk/2014, last accessed 15 February 2019.

[31] Robbins et al, "Mapping."

[32] Spaargaren and Mol, "Sociology, Environment and Modernity;" Hajer, *The Politics of Environmental Discourse*; Huber, *New Technologies and Environmental Innovation*.

The following four sections present each case in turn, gradually building a picture from each case. We then attempt a more general analysis and conclusion concerning shifts in knowledge practice and communities. Our case study approach rests on Yin who suggests that research case studies can be descriptive, exploratory, and/or explanatory.[33] Our cases aim to be all three.

Case 1: Improved Access to Urban Water Services for Over a Million People in Uganda and Other Developing Countries

The case concerns development-oriented engineering that addresses an important developmental and social issue – the provision of piped water to poor, informal, urban settlements in developing countries. The Loughborough University Water Engineering and Development Centre (WEDC) conducted research with the Ugandan public utility, the National Water and Sewerage Corporation (NWSC), to identify how the reach of piped water in Uganda could be extended sustainably to many more people. Sustainability in this case met the twin challenges of financial and budgetary constraints and quality concerns. Only an estimated 16% of the sub-Saharan African population uses piped water and other sources are highly susceptible to contamination, especially in urban areas[34]. WEDC research with NWSC led to improved urban water provision for over a million people by 2011. The following paragraphs illustrate how new and diverse knowledge, new models of practice, and their dependency on a robust community of practice combined to make the case a good example of borderlands engineering.

Water engineering is usually classified as a sub-area of civil engineering, but is also in its own right a major area of interdisciplinary knowledge and practice. The engineering *knowledge* in this case is diverse. It includes innovative research knowledge concerning how to substantially increase access to water in poor urban areas. The WEDC leading actors describe their work with NWSC as providing sustainable engineering services, not only construction engineering to provide “kit” such as hand pumps. It concerns all the different interventions that are required to make the machinery sustainable. This undervalued engineering knowledge includes evaluation of delivery solutions for water through pipes. It includes systematic understanding of user groups using surveys, interviews and focus groups. The water engineers involved are well regarded but are rather ambivalent about how much of their work is “real engineering.” One of the engineers plays down the science and also the socio-economic knowledge as not an integral part of real engineering: “Engineering has been somewhat of a lesser player than science and economics and social studies.”[35] “We provide

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[33] Yin, *Case Study Research*.

[34] 26% of urban dwellers, and 3% of rural dwellers, Interagency and Expert Group on MDG Indicators, *The Millenium Development Goals Report 2012*.

[35] Interview with Sam Kayaga, conducted by Gordon Wilson, July 25, 2016.

service improvement in terms of increased access to piped water, quality access through shortened delivery times and sustainability. It is not just about providing kit. It is about all the different interventions needed to make the kit sustainable."[36] These water engineers have no doubts that their engineering work is central to the problem-solving needed for water service delivery. But they exhibit self-doubt about how central their work is to "normal" engineering.

The nature of borderlands engineering *practice* in this case focused on two elements. First, water safety; and, second, assessment of utility meters, meaning not only technical specifications but also socio-economic assessment given the extreme sensitivity of users to cost. Low-income families have an average income of less than $2 a day. New models were developed to extend and improve water service delivery to those previously unserved. As a result, in Uganda, an additional 526,000 people gained access between 2000-2011 of which 196,000 resided in urban informal settlements. The engineering provided improved water quality, greater equity in provision, and reduced travel and waiting times especially for women and children via shared connections at standpipes. Furthermore, through the work of NWSC's External Services Department, the research benefits were transferred to other countries, including to Kenya, Tanzania, India and Zambia.

The origins of the case may be found in a long-standing *community of practice* in water engineering, where the actors largely speak the same practice language and possess a similar culture. In particular there are strong ties between the WEDC and the NWSC, which started when both were involved in a World Bank infrastructure project in 1988, during the UN's First Water Decade (1981-1990). WEDC academics have taught many who now work for NWSC, as PhD and Masters students and on short courses. The NWSC is a world-leading water utility with, for example, a major contract to improve services in Bangladesh's second city Chittagong. The joint lead at WEDC Loughborough is Ugandan, worked previously for NWSC, and did his first degree at the national university of Uganda – Makerere – with which WEDC also has strong links. He has many colleagues there. "I'm an ex-staff member of NWSC where I think in 2002 we were providing services to about 14 towns. But now they have expanded to over 100 towns in Uganda. This has helped articulate their philosophy to the extent that that are part of a world leading water utility including providing services to Asia."[37]There are also links with UK institutions connected to water engineering, for example, Cranfield University. Beyond the community of practice, the WEDC academics involved in this case are at the hub of a *water engineering network*, where, through a shared discourse, there exists a "background consensus that lies behind all narrative exchange."[38]

To summarize, this E4D case emphasizes:

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[36] Kayaga, op cit.

[37] Kayaga, op cit.

[38] Fischer, *Democracy and Expertise*, 201.

- The engineers involved, clearly world-class in knowledge and practice, are very ambivalent about whether what they do is truly innovative. The self-doubt of many development engineers is a key element, where borderlands E4D thinking is seen as a marginal activity, not yet central to engineering.
- A major systemic advance has been made to improve the livelihoods of urban water users in ways that are financially sustainable, by developing a diverse set of borderland processes and practices that are "messy" but effective.
- Delivery takes place via a long-standing community of practice, a network of trusted and hard-working engineers from Loughborough, Makerere, and around the world, within a "water engineering network."

Case 2: An International Disaster Monitoring Satellite Constellation (DMC) Spin Out

The Disaster Monitoring Satellite spin-out company from Surrey University has fundamentally changed the economics and capabilities of imaging the Earth from space by small, low cost earth observation (EO) satellites with innovative on-board cameras to provide a rapid-response, global imaging service. Approximately 200 major disasters occur globally each year and the DMC responds to approximately 20 such disasters annually worldwide. The UN estimates that the DMC has aided over 250,000 disaster victims. The DMC provided the first comprehensive coverage of the Asian Tsunami disaster in 2004 and the first images of the Katrina hurricane disaster to US authorities. It also supports public agencies in Brazil to provide annual Amazon basin deforestation assessments, and most recently has provided two-weekly Amazon basin images, increasing the ability to identify deforestation at an early stage and alert authorities to logging. In a clear case of ecological modernization, the monitoring service is provided free of charge, the income coming from commercial exploitation of excess capacity of the satellites to provide other information. Another source of income is to provide space engineering capacity building in partner countries. Surrey has trained staff to set up six national space agencies.

The key to the practical earth observation constellation has been the development of small satellites and imaging sensors using the latest "commercial-off-the-shelf" technologies and devices. Six Earth observation (EO) micro/mini-satellites have been designed and built by Surrey Satellite Technology Limited (SSTL), the Surrey spin-out company, between 2003 and 2010 to create the international Disaster Monitoring Constellation (DMC). The six micro spacecraft were launched by different countries (the UK, China, Algeria, Nigeria, Turkey, Spain) to provide free, timely information about disasters. The constellation of connected satellites allows for 24-hour monitoring across the globe.

Space activity at Surrey University is highly multidisciplinary. Electronic engineering is the core discipline, together with astrodynamics, mechanical engineering, geography, and soil science. The engineering *knowledge* involved is complex, technically based on miniaturization in electrical engineering with strong socio-economic components. The design, construction, and operation of the DMC depends on a complex range of research into satellite platforms covering: (a) the modular mechanical structure, (b) thermal models and designs, (c) power systems, (d) on-board data handling systems and mass data storage, (e) communications systems, (f) agile yet precise three-axis control systems, (g) imager stabilization techniques, (h) electric-resistojet butane propulsion system for orbit manoeuvring, (i) autonomous orbit determination and precise positioning, and (j) astrodynamics analysis for optimal orbital constellation control and maintenance. Essential to the DMC is the development of very wide imaging cameras taking innovative advantage of the latest sensors, processing, and mass storage components to achieve high quality imaging from a small and relatively inexpensive satellite. SSTL launched the world's most advanced and capable mini-satellite (NigeriaSAT-2) in 2010 at about 1/20th of the cost of conventional satellites. The case then is of sophisticated engineering, and at the same time involves simplification from the big engineering of "normal" space engineering. E4D in this context may be summarised as simplified sophistication.

Our analysis suggests two key innovations that illustrate the nature of E4D as borderlands activity. First, the knowledge and *practice* surrounding small satellites. The case has taken much of what already exists (micro-spacecraft and monitoring technologies) and translated it into a configuration that is fit for a new purpose. What is new is the configuration that goes beyond the single stand-alone satellite. A single satellite has limited imaging area capability, so to image a specific point on the earth may take days. With a coordinated constellation of satellites, the orbital dynamics means that one satellite will cover any part of the earth within 24 hours. In this, the team required a good knowledge of how monitoring technologies work in the harsh environment of space, while minimizing spacecraft size to make everything more affordable. Big and high technology is replaced by small and flexible technology. As Martin Sweeting stated:

> It would have been possible to have a constellation of six satellites before of course but the cost would have been prohibitive. What we did at Surrey was to miniaturize the space craft, reduce the cost dramatically by a factor of 10 or 20 and therefore become economically practical to have a constellation to meet the requirements for disaster monitoring.[39]

The case explicitly moves away from a risk-averse military model of satellite development to a more evolutionary, open style of engineering practice with room for error. The nature of E4D here is accepting of a certain level of risk in order to facilitate innovation, flexibility, and agility.

The case highlights the benefits of changing a dominant paradigm with respect to space research. When researchers went to business conferences in the 1980s small satellites were seen as of little use. "We have developed a whole new species of spacecraft and

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[39] Interview with Martin Sweeting, conducted by Gordon Wilson, July 20, 2016.

approach to space … small, low cost, highly capable satellites. It was considered a pretty crazy concept, generally of little use."[40] The Surrey team played an active role in changing the perception so that small satellites are now fashionable.

To complete the borderlands nature of the case, project leader Martin Sweeting and his team have developed a strong *network* over two decades among partner countries. Academic culture has played an important facilitating role through conferences where knowledge has been shared and through the training of overseas students at Surrey. Developing country engineers have been integrated into a strong knowledge and practice network. Access to space technology for developing countries, on an affordable budget, is a major success. There is a major emphasis on capacity building in space engineering for developing countries.

To summarize:

- the new form of E4D knowledge is the reconfiguration of already existing products based on constellation building and miniaturization to fit satellite technology for developing country purpose.
- the key innovation is the constellation of a set of small, cheap satellites equipped with robust monitoring equipment into a powerful array to improve disaster monitoring around the world.
- there is a strong focus on network building through capacity building in space engineering for developing countries.

Case 3: Removing Arsenic from Groundwater

The engineering problem in this case is the chemical conversion of relatively insoluble arsenate by nutrients in groundwater to produce relatively soluble arsenite – an unintended consequence of modernized agriculture, especially rice which requires significant amounts of irrigation water. At least 137 million people in 70 countries consume arsenic-laced groundwater due to shortage of safe drinking water.[41] The conventional technologies for arsenic remediation are based on "pump and treat" methods involving either adsorption or membrane processes. Such plants are expensive to run and have problems associated with waste disposal and maintenance. In contrast, Subterranean Arsenic Removal (SAR) treatment neither uses any chemicals nor produces waste, making it a very low-cost technology option for rural use. This technology can replace expensive adsorption or membrane-based processes where disposal of high-arsenic hazardous waste poses a serious problem. Very low operating costs make the process affordable.

A team led by Bhaskar Sen Gupta installed the world's first chemical-free water treatment plant in the arsenic belt of India to benefit rural people living on per capita income

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[40] Sweeting interview.

[41] Cambridge Arsenic Project, "Predicting the Global Distribution."

of less than 1 US$ a day. With nine facilities in India, Cambodia, and Malaysia by 2013, more than 13,000 people received their water supply from Subterranean Arsenic Removal (SAR) plants. Many villagers who started using clean water from the community plants in 2008 have shown significant signs of recovery from chronic arsenicosis.

The science of arsenic in groundwater is well-known. Sen Gupta's contribution has been to innovate to make removal using natural bacteria viable. The engineering *knowledge* is based on promoting the growth of arsenic-oxidizing bacteria in the aquifer, which in turn dissolves arsenic into sparingly soluble form and returns it to the soil under oxidized conditions. The oxidation processes are accelerated by the autocatalytic effect of the oxidation products and by the natural bacteria. No sludge is produced in the process, maintaining normal permeability of the aquifer.

The borderlands nature of this knowledge is reinforced through its combination with knowledge concerning cost effectiveness, and the lead researcher's tacit knowledge of how arsenic decontamination plants may be sustained in resource-poor areas. Thus, the engineering design considerations were tightly constrained. In order to ensure application of the arsenic remediation technology in resource-poor areas, the following conditions were key: (a) marginalized rural communities may not be able to pay more than 1 US$ for a month's supply; (b) they may not be able to pay for regular maintenance, chemical supplies, waste disposal, and other recurring costs; (c) the technology should ideally be waste-free. All plants are designed to produce safe drinking water without the use of any chemicals, adsorbents, or membranes and without waste generation.

Thus, all treatment plants can operate on electricity, solar, or wind power, which makes them suitable for use in remote areas with no access to grid power. Plants have a very long life; submersible pumps can run for 25 years with very little maintenance and every component used in the plant is available from local hardware shops. The impact is primarily provision of safer water at a low cost to poor rural people.

This example of successful E4D borderlands *practice* results from a combination of excellence in chemical engineering and strong attention to the development context. It represents a case where engineering excellence is integrated with development practice that brings social value with low environmental impact. Sen Gupta's team has produced a practicable engineering solution, working with what is there.[42] The innovation has won a series of prestigious prizes. The jury of the UK Environment and Energy Award said: "The judges felt this was a highly innovative technology based on a thorough understanding of the biogeochemical principles of arsenic outcome and transport in groundwater. It takes full account of the technical and financial constraints of the areas of the world where arsenic groundwater contamination is a significant human risk. The low tech nature of the installations coupled with the minimum waste disposal and energy requirements set the

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[42] Lourides, "Design as Bricolage."

standards in sustainable remediation." Prize success has significantly increased the reputational impact of the innovation.

The technology was developed by a *network* of Indian and European engineers (the third element of E4D as borderland activity), led by Bhaskar Sen Gupta in 2004-06. The initial research partners were Queen's University Belfast (Sen Gupta's university at that time), Stuttgart University, Leiden University, Miguel Hernandez University in Europe and the National Metallurgical Laboratory, Institute of Environmental Management and Studies, and Ramakrishna Vivekananda Mission from India. More recently, the team has worked with Royal University of Phnom Penh, Bengal Engineering and Science University, University of Malaya, and National Metallurgical Laboratory of India for large scale implementation of the project. Sen Gupta has formed an NGO and developed significant alliances with other NGOs.

In summary, the case illustrates well the elements of E4D as borderland activity:

- The engineering knowledge addresses a major problem of development: addressing toxicity from non-piped water by increasing knowledge of arsenic remediation. Prizes were important in building the reputation of the research and the researcher.
- The practice breakthrough is the development of pilot plants and diffusion to sites in three countries, learning with each site. The plants create no waste and have low energy demand and maintenance.
- The researcher has used a wide range of academic and applied contacts to build an academic network, and has also set up an NGO to build the plants.

Case 4: Low-energy Design Strategies for Healthcare Buildings in a Changing Climate

A Cambridge University team has investigated the potential of passive cooling and natural ventilation to regulate temperature, initially in health service buildings. Through inhabiting a borderlands space, their research on low-energy strategies for ventilation and cooling of non-domestic buildings has continued for over twenty years, producing new engineering *knowledge* on natural ways to control temperature.

The initial work in natural stack ventilation and passive cooling (completed 1990) undertaken by Professor Alan Short and colleagues won first prize in *Architecture Today*'s High Architecture, Low Energy Awards 1992. Short and his team evolved the approach further to deliver cooling benefits by the introduction of Passive Downdraught Cooling (PDC). This low-energy technique distributes pre-cooled air into buildings without mechanical fan assistance, extending its range. The underlying principles of the technique were explored using physical models, and its performance was predicted using thermal modelling.

The team has developed design principles based on constructing new and diverse knowledge with respect to what is there, in this case existing buildings and air flows. It is typical of borderlands knowledge. Thus, a study of a 1920s traditional heavyweight masonry block revealed the unexpectedly significant resilience of cross-vented open ‘Nightingale’ hospital wards. Promoted by, and strongly associated with, the pioneering UK nurse, Florence Nightingale, these large, multi-bed wards originate from the mid-19th century. “There are nearly 2,500 [Nightingale Wards] left and they are heavy masonry buildings, high ceilings. Florence Nightingale was very specific in her descriptions of what they should be like.”[43]

This study demonstrated that significant resilience to overheating in the face of changing climate – and also energy savings – could be achieved by light-touch measures. The team has since examined the complexities that arise in buildings for healthcare, such as resilience in heatwaves, prodigious internal heat gains, vulnerable occupants, and airborne cross-infection concerns. Outside the UK, the team has collaborated with the Indian Ministry of Health and Family Welfare (MoHFW) led by its Chief Architect, Professor Chandrashekhar, to develop a resilient prototype 200- 300 bed hospital, to be the basis of 600 hospitals planned across India by the ministry.

In terms of borderlands *practice*, this is a case of a paradigm-changing engineering innovation to produce very low-energy non-domestic buildings. The challenge to conventional healthcare building design, and generally to the prevailing modernity of closed, controlled environments, is overt. Short states that he and his team were “regarded as complete idiots” when they started.[44] However, the team has been able to produce an alternative evidence base, for example in relation to the health challenges of hospital wards and operating theatres. Applying this evidence base to new buildings, Short notes: “Modern architecture tends to be very lightweight and has low thermal mass so it attracts the outside temperature.”[45] Thus, with colleagues from various institutions, he began designing very different buildings that applied passive cooling (or heating) to hospital design. Short, along with colleague Brian Ford, designed a down-draught-cooled laboratory building in Ahmedabad many years ago.

The engineering innovation, based on borderlands new knowledge and practice, has required an interdisciplinary *network* and community of practice. Short’s team in Cambridge, together with Andy Woods and colleagues from the BP Institute, models air flows in buildings and use of water and air. Co-investigators at Loughborough University collect data and model temperature and humidity behavior over long periods together with air flows. Through all of these activities, physical modelling is preferred over computer modelling: “It’s fantastically complicated … it’s fantastically interdisciplinary.”

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[43] Interview with Alan Short, conducted by Gordon Wilson, June 16, 2016.

[44] Short interview.

[45] Short interview.

The Cambridge team is at the hub of different types of partnership. The aforementioned academic group of Cambridge, Loughborough, and the BP Institute is strong on data modelling, physical modelling, and fluid mechanics. There is also a socially, broadly based community of practice with interests, values, and commitment to building design advocating paradigm change.

In summary:

- This case represents borderlands activity because it involves starting with enhanced knowledge concerning what is there, layering in new practices, and building on strong networks of research, development, and use. The paradigmatic innovation is to build knowledge of passive cooling (or heating) of hospital designs as an alternative to high-tech air conditioning systems and closed buildings.
- Researchers start with existing buildings and air flows, and then develop new practices to solve specific user problems. There are two types of network: a research network; and a community of practice around changing the paradigm of building design.

Discussion and Analysis

The relative lack of analysis of E4D in the literature is indicative of its marginality to mainstream engineering. Our research suggests, rather, that it is an important, common, and wide-ranging activity done by socially conscious engineers and colleagues. E4D deserves better analysis. The cases here give a picture of E4D and development engineering as activities in borderlands spaces where new knowledge, practices, and communities are being built. However, in its knowledge and practice, it is often seen as on the margins of "normal" engineering, even in the perceptions of development engineers themselves, as evidenced in the cases presented in this article. We analyze these spaces through three categories – knowledge, practice, and communities – and conclude with a discussion of their meaning for post-normal engineering.

Knowledge

The case studies suggest new engineering for development (E4D) learning and knowledge building that usually combines interdisciplinary and complex knowledge generation.

We have three insights. First, there are elements of long-standing engineering knowledge but also evidence of moves towards the shaping of new *paradigms* that assist in the characterization of E4D. In the urban water services case, for example, knowledge of consumer behavior was integrated into water engineering knowledge so as to allow a massive scale-up of benefits. In the disaster monitoring satellite case, the paradigmatic shift in knowledge was the miniaturization and constellation building of small cheap satellites that has made disaster relief possible and timely. The change brought not just a new disaster assessment tool but also allowed sophisticated knowledge of satellite engineering to be more easily transferred to developing countries. The arsenic remediation case also used (tacit) knowledge of consumer behavior, producing an elegant, low-cost alternative to “pump and treat” engineering knowledge. In this, it potentially changes the engineering paradigm in an ecologically more sustainable way. The low-energy building design case demonstrates the feasibility of moving from “normal” high-tech air-conditioned, closed building design to open and passive processes. In each case new engineering knowledge is being constructed by mixed teams of researchers working in borderland spaces. In all cases the result is improved cost effectiveness, environmental sustainability, and/or human development.

Second, in all cases, the new paradigms being shaped bring integrated knowledge, both technical and social, involving multidisciplinary and interdisciplinary approaches to research as well as to the evolution of new borderland practices. The new knowledge crosses disciplines and involves complex problem solving towards application in international development situations. The access to urban water case integrates technical knowledge of water systems with utility and service management, and research on the systemic nature of governance of water in low-income situations. The “devil is in the detail” here, where ability to make sense of messy social situations is important given that there are no silver bullets (no available equipment that would solve the problem). The engineers talk of “making the best for the situation on the ground.” The disaster monitoring satellite case cites not only electronic engineering but also astrodynamics, mechanical engineering, geography, and soil science as key disciplines to enable the building of working satellites 10-20 times cheaper than “normal” large satellites. The lead researcher of the arsenic remediation case spoke of his “distributed expertise,” including knowledge of “working with what’s there” so that all components can be found in local hardware shops. The low-energy building design case illustrates the importance of strongly interdisciplinary research that aims to “upend” the paradigm of “modern architecture and its effect on energy systems.” The result is new design approaches for low-energy non-domestic buildings, but also interdisciplinary research to disprove some of the key tenets of the “modern” school, such as that enclosed environments are best for infection control. This is a crucial research knowledge result if developing country building environments are to be improved. This is also a unique knowledge domain of development engineering that is very different from “normal” engineering, blending working with what is there, the social and economic context, and engineering principles.

But third, there is ambivalence about the engineering knowledge originality of the work. The perceived marginal and borderland nature of the activity elicits ambivalence and self-doubt among engineers, though this is balanced by excitement, ambition, and promotion. Just one case unequivocally projected itself as paradigmatic and world-shattering in impact – the passive cooling hospital design case. Though the Surrey satellite case is also a paradigm-changing case, with its vision of simplification leading to a major reconfiguration innovation, there was irritation that it was not seen as “best engineering” by national research funding agencies, which required constant refutation. The Surrey satellite, access to urban water, and arsenic remediation researchers, however, all suggested in different ways that their focus was on pulling together already known products into something new and useful. In this, they implied that their work was not "best" engineering as judged by "normal" criteria (see Introduction). The urban water researchers also stated unequivocally that their work was "not real engineering," much as Trevelyan found.[45] This self-doubt arises even when, as we have demonstrated, the receipt of prizes shows that the engineering is anything but dubious.

We suggest that the perception of E4D as marginal, borderlands engineering is the reason for self-doubt. The self-doubt of many development engineers may hold back this emerging sub-area of engineering knowledge. Trevelyan's data suggests that most engineers, not just development engineers, think they are not doing much engineering, but are able to undertake a wide variety of diverse tasks.[46] He also argues, however, that they could not do their jobs and deal with these diverse tasks without their engineering background and expertise. They have embodied within them a diverse range of knowledge and skills. The urban water case study researchers exemplify this when they claim that because they are engineers they knew about technical specifications of pre-paid meters and could assess rapidly what would be needed. The pre-paid meters had to be adapted to suit local conditions and the wider Ugandan context in order to be sustainable. Thus, they consider E4D as an element of "How can we adapt what is being done elsewhere to the local context?"[47]

When the E4D researchers imply that their major breakthroughs are not really engineering, they reiterate a well-known trope in development studies and practice: namely, that engineering interventions by themselves are not sufficient for economic or human development because they ignore the multi-faceted challenges of practice, which may be economic, social, political, and cultural in nature. Such interventions are often described as "technocratic," in particular when they ignore political dimensions.[48] What they are not articulating or celebrating in their work is that significant knowledge creation is tied to human development goals. That knowledge creation is perhaps why they all gained major prizes in engineering even as they modestly suggest, incorrectly, that their work is not that original.

The evidence from the cases suggests that a new style is emerging. The characteristic knowledge generated in the borderlands of disciplines introduces new ways of thinking that fall within the rubric of "post-normal" engineering.

Practice

The cases provide evidence for insights concerning E4D practices where new practice paradigms emerge in the search for impact on human development goals. The search for

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46 Trevelyan, "Reconstructing Engineering."

47 Kayaga interview.

48 Wilson, "Beyond the Technocrat."

engineering solutions to problems of the world's poorest influences value models and shapes new approaches to eco-modernization in the borderlands where engineering evolves to solve pressing development problems.

The access to urban water services case illustrates the building of new practices that sustainably extend water provision in Uganda, and potentially elsewhere, thereby improving quality, equity, and travel and waiting times largely of women and children. The search to extend water access to the poorest brought new practices that combined technical aspects of utility meter design with a model for social equity and financial sustainability. The Disaster Monitoring case illustrate another paradigm change in engineering practice: the viability of small, flexible satellites integrated in constellations shows the utility of open technology instead of the "classic" rigid high-tech big satellite engineering practices of the major space agencies. These new borderland practices allow the development of a set of engineering practice routines in developing countries that would not have been possible under previous conditions.

Sen Gupta's contribution to arsenic remediation has been to innovate so that arsenic removal using natural bacteria becomes viable. His invention is a practicable engineering solution that solves the problem of both technical and financial constraints of low-income communities. He works with what's there, which leads, for example, to innovatory practices that provide flexibility in choice of electrical energy source, in this case allowing the plant to work off solar power where conventional electricity is not available.[49] Practices also include the use of local materials where possible. The case is an exemplar of how important it is to institutionally embed a successful and potentially sustainable new practice. The radical redesign of hospitals has the potential to begin a paradigm change in practice, though resistance will be extremely strong. The driver is the desire to shift policy towards improved human development and well-being, through improved low-energy systems with lower maintenance practices in non-domestic buildings of both the developed and the developing world.

To gain credibility and legitimacy both in terms of excellence and engineering practice impact, the engineers in these cases have pursued prizes, many of which have been awarded because of innovative borderlands practices developed to make engineering suitable for poor and isolated populations. Prizes act to celebrate not only excellence but also indicate paradigm shifts and originality.

Analysis of the cases illustrates that E4D results in new borderland engineering practices to solve problems that affect the poorest people and poor regions of the world. The major insight is that new value models are needed if new practices are to become sustainable and not dependent on short-term project-based aid donations.

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[49] Lourides, "Design as Bricolage."

Engineering practices need to evolve to encompass the restricted economic means of the poorest billions. The access to urban water research program integrated socio-economic thinking and in-depth analysis showing the extent to which dwellers might be willing to pay something towards clean water in an environment where public support and subsidy was very limited.[50] The main drivers of the engineering research were human development and environmental health concerns, rather than economic value and environmental stewardship *per se*. However, costs had to be incorporated into the sustainable development model, with the knowledge that users were prepared to pay for access to safe water. This resulted in the installation of utility meters at additional standpipes, which work on a prepayment system.

The disaster monitoring case developed cheaper constellation satellite systems to bring down costs. Importantly, it also developed secondary use of the system, a practice that provides what are essentially environmental services while obtaining economic returns.

The arsenic remediation case illustrates a major concern for financial sustainability if scale-up is to be achieved. The engineers in this case are attempting to fund investment by users of decontaminated water paying an affordable fee for the service. The success of the new approach leads to a challenge, however. Other than the clean water that the engineers feel should be provided free to poor users, there is little left to sell which would attract private service delivery institutions.

Thus, the evidence from the cases suggests that new forms of value creation are emerging and that knowledge generated in the borderlands of engineering and social disciplines, in uncertain environments where the poorest live and work, generates new practices. The engineering paradigm shifts come from integrating the technical with the social to resolve development problems.

Networks and communities of practice

Engineering novelty is the result of work in interdisciplinary networks and communities of practice. These constitute important supportive structures in borderland spaces. The water engineering *network* around the Loughborough Water Engineering and Development Centre (WEDC) and the Ugandan National Water and Sewerage Corporation (NWSC) is a longstanding *community of practice* built on mutual understanding and values, cemented by a large postgraduate training program that has led to major joint projects around the world. It is a case of longstanding mutual north-south cooperation style of collaboration that has changed the way water engineering has been practiced.[51]

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[50] Robbins et al, “Mapping.”

[51] The concept of north-south cooperation is presented in detail in Robinson et al. *Managing Development*.

Surrey University is at the hub of an international satellite and space network that has changed the way that satellite engineering is practiced. The consortium for building the satellite constellation includes agencies in six countries together with very significant human capacity building through formal postgraduate education.

Professor Sen Gupta is at the hub of a borderlands network of Indian and European Engineers and development NGOs. The initial research, in 2004-2006, brought together four European universities, two Indian research institutes, and an Indian humanitarian NGO. More recently, Sen Gupta has worked with the Royal University of Phnom Penh, Bengal Engineering and Science University, the University of Malaya, and the National Metallurgical Laboratory of India for large-scale implementation of the project. He formed an NGO with significant other NGO alliances to focus on pushing for acceptance and support for the new engineering practices.

The low-energy hospital building case is based on an academic research hub integrating three groups that together constitute a borderlands space (Cambridge, BP Institute, and Loughborough) which is further enriched by a broader based community of practice around building design. Partnerships have been built organically over time and now constitute a significant interdisciplinary and multidisciplinary community that has built a significant evidence base to advocate for paradigm change.

Overall, rather than "best" engineering being in opposition to "appropriate" engineering and the mess of bricolage, we see the emergence of a new engineering approach. Borderlands are sites of cooperation, messiness, mixing, and hybrid identities. The networks and communities analyzed here contain a complex mix of multidisciplinary and interdisciplinary expertise. They are driven by human development objectives of social action. The development and social engineers here explicitly see themselves as social actors, and often as social activists, building networks and communities to develop new engineering practices for international development, in conjunction with new products and processes.

E4D as Borderland Activity

We have suggested in our analysis of E4D knowledge, practices, and networks that there is evidence of new styles of interdisciplinary thinking, new practice paradigms, and complex borderland spaces of cooperation, mixing, and hybridities. The concept of post-normal engineering is useful in supporting borderlands approaches, we think, in that it allows us to get beyond the well-worn perception of E4D as relatively marginal and "second best" engineering. E4D, then, may be seen less as a marginal space but more a borderland space in knowledge and practice where a variety of technical and non-technical communities work together for largely social goals. Within this space, our results illustrate the emergence of a new set of E4D practices: new ways of doing things and responding to complex human needs and situations. We see the growth of what often begins as "one-person bands" of engineers who try to do something different, sometimes ploughing their own furrow but looking for like-minded co-operators and collaborators. Largely emerging from these practices, we recognise the development of, and focus on, a new form of engineering knowledge within the borderlands space. Crucially, this new knowledge allows insights into engineering more generally and how it could become more socially and institutionally aware.

It is clear from our results, therefore, that E4D requires knowledge not only of "normal" engineering concepts but of the complex and uncertain environments in which engineering solutions are sought, where the range of problems can be extremely diverse and broad. In this sense it falls within the rubric of post-normal engineering. Generally speaking, post-normal engineering challenges the ability of normal engineering to deal with complex real-world problems of climate change and changing the situation of the very poorest. Inquiry into such problems through reduction into constituent parts reveals at best only a partial understanding of the whole.[52] However, E4D still encounters other problems of being post-normal, such as the small-scale and borderland nature of knowledge and practice. But we do see examples in our cases of the beginnings of scale-up and the integration of networks and communities.

Conclusions

Our results suggest that our approach to the study of E4D as borderlands allows us to understand major problems within engineering so that we avoid assertions often made in development studies that the product/artifact takes precedence over the process, and/or that the technical dominates the social. The engineering teams we studied are well analyzed using the borderland metaphor, in that they act in the spaces of various types of technical and social activities. Although we see a constant tension between the technical and the social, these cases show major and honest efforts to overcome those boundaries. If we conceptualize this tension as a permeable borderland issue we can begin to value a wide range of engineering knowledge and practice.

Many engineers were rather modest about what they were doing, often saying that it was "not real engineering," but at the same time most were keen to demonstrate the paradigm shifts that their work envisioned. Self-doubt may hold back the development of this sub-area of engineering. While these cases were selected for their excellence, they show that even very successful engineers are not completely confident in their assessment of their work. Is this a general problem with engineering, as Trevelyan suggests, or is it a more specific problem with those sub-areas of engineering knowledge and practice that are often judged as more marginal? Perhaps both, and it certainly needs to be addressed if borderlands E4D work is to become central.

The work of development engineers in our study shaped and shifted the environment, rather than attempting to control or defeat it. Practices were highly multidisciplinary and/or interdisciplinary with a range of means to apply the research, such as setting up NGOs and

[52] See for example Abbott and Wilson, *Lived Experience*.

spin out companies. Networks were extensive and eclectic, culminating in building significant communities of practice. They tended to be less focused on “value creation” in the strict business model sense (although they were aware of the need for financial sustainability), and more concerned to build social value.

E4D takes place in a borderland space where networks and communities work towards largely social goals, albeit searching for sustainability in an eco-modern style. This space contains new engineering knowledge with insights into how it could become more socially and institutionally aware – a new kind of “post-normal” engineering. Our study began with a focus on what constitutes excellent E4D and development engineering, but it has also brought insights into new ways of thinking about engineering *tout court,* especially engineering at the boundaries of new and improved products and processes. We suggest, then, that our key concepts define the activities that take place in permeable borderland spaces.

Acknowledgements

To the Open University for fieldwork funding. To Drs Sam Kayaga, Kevin Sansom, Sen Gupta, Alan Short and Martin Sweeting and their colleagues, for sharing their engineering for development knowledge and their case studies. To Paul Nugent, Cyrus Mody, Dean Nieusma and anonymous referees for their incisive and useful comments.

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