Engineering Practice as an Emerging Field of Inquiry: a Historical Overview

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Abstract:
Perception of the nature of engineering practice is an aspect of technology literacy of direct interest to engineering educators, one that impacts a variety of actors: potential and present engineering students, engineering faculty and the general public. This paper contributes to scholarship in the areas of technology literacy and engineering practice studies by presenting a timeline of empirical studies of engineering practice carried out in the US, Europe and Australia from the 19^{th} century to today. We observe a notable widening of the range of research approaches employed to capture what engineers do and an increasing recognition that sociotechnical aspects of engineering work play an important role in the workplace. We conclude by setting out some implications for educators of the empirical findings from of this area of scholarship.

1. Context

At a symposium entitled Engineering as a Social Enterprise organized by the US National Academy of Engineering in 1990, Walter Vincenti pointed out that "engineering functions inseparably from the society of which it is part" and he went on to suggest that "to perform engineering's task as a social enterprise" engineering practice needed to be better understood (Sladovitch 1991, p. 2 – 4). In the intervening years there has been a growing body of empirical data about this topic. Thus the nature of interactions taking place in enterprises between engineers themselves and interaction with other colleagues and with clients have been a focus of study (Barley, 2005; Bailey and Barley, 2010; Bucciarelli, 2003; Vinck, 2003; Faulkner 2007; Downey 1998). Trevelyan (2013) gathered data on engineers working in Australia and SE Asia and concluded that sociotechnical aspects of engineering work such as technical coordination are essential features of successful engineering performance and require skills that go well beyond the traditional engineering science competences espoused in the Grinter Report (1955). Nevertheless as will be shown later as this research has been dispersed in a variety of fields such as organization science, engineering studies, sociology, anthropology and ethnography it has been difficult to arrive at a global portrait of what engineers do.

There has simultaneously been an increasing awareness of the need for engineering practice to more effectively inform the practice of education and training. The ASEE has taken a lead in this process and we note that its Transforming Undergraduate Education in Engineering program has underlined the importance of developing a new strategy for undergraduate engineering education to meet the needs of engineering of industry in the 21^{st} century (ASEE, 2013).

2. Research Question

What insights can a timeline approach to the evolution of engineering practice research provide? The question is of an exploratory nature and can be classified as an example of the US National Research Council's category of *Description—what is happening* (National Research Council, 2002, p. 70)

3. Engineering Practice – An Emerging Field of Study

Peter Fensham (2004) published a framework with which to judge the evolution and maturity of science education research. It involves 14 criteria which are grouped into three broad categories: structural, research, and outcome as shown in Table 1.

TABLE 1: FENSHAM'S CRITERIA FOR SCIENCE EDUCATION RESEARCH EVOLUTION

Category	Criteria
Structural	Academic recognition, Research journals, Professional associations, Research conferences, Research centres, Research training;
Research	Scientific knowledge, Asking questions, Conceptual and theoretical development, Research Methodologies, Progression, Model publications, Seminal publications;
Outcome	Implications for practice

This framework was adopted by Froyd and Lohman (2010) to argue that engineering research has become an established field and they supported this claim by presenting a detailed timeline of research in the field from 1973 onwards. Later Williams (2015, pp 87- 90) adopted the Fensham framework and marshalled data to claim that engineering practice was poised to emerge as a field of inquiry. He detailed research criteria from the framework which were being satisfied although he observed that as yet there is little evidence to support a claim that structural criteria were being met in this area of research.

Williams (2015) compiled a timeline of notable empirical research in the field of engineering practice and this study complements his argument and provides scholars and engineering professionals with an opportunity to consider the strength of the claim. At the same time, a study of the findings and the trends revealed in the empirical research thus captured chronologically provides useful pointers as to how this field of inquiry can contribute to decision making by engineering educators and trainers.

4. Timeline of empirical studies

Preliminary note: The timeline below aims for representativeness rather than completion. Although many of the scholars cited have been responsible for numerous contributions to the field, to facilitate the reading and interpretation of the chronology we have limited ourselves to providing just one contribution from each of the authors cited; additional work is cited in the contributions/findings column in some cases.

YEAR	PUBLICATION			CONTRIBUTION/FINDINGS
	Book	**Journal article/ book chapter**	**Report**	
1911	Taylor, F. W., *The Principles of Scientific Management*, New York, NY, USA and London, UK: Harper & Brother			Scientific management approach proposed for industrial processes
1917	Fayol, H., *Administration industrielle et générale; prévoyance, organisation, commandement, coordination, controle*, Paris, H. Dunod et E. Pinat,			Industrial management proposals for the mining industry
1933	Mayo, E. *The human problems of an industrial civilization*, Cambridge, MA: Harvard.			Research led by Mayo into productivity in spinning mills and other industrial contexts in the Hawthorne Studies was an early example of observation studies in the manufacturing workplace
1960	Barnes L. B., *Organizational Systems and Engineering Groups*, Harvard School of Business, Cambridge Mass.			Suggested innovation is dependent on organizational structure
1961	Burns T. and Stalker G., *The Management of Innovation*, Tavistock, London			Suggested R&D staff had difficulty communicating with manufacturing dept.
1961			Langton, N., The Teaching of Theoretical Subjects to Students of High Polymer Technology. 2 Vols. A Report to the Nuffield Foundation. London	Collected detailed descriptions of the techniques, processes, instrumentation, and design procedures used by firms through interview and brief observation of polymer technologists and derived a theoretical curriculum.
1966		LeBold, W. K., Perrucci, R. and Howland, W. E., 'The Engineer in Industry and Government," *Journal of Engineering Education*, vol. 56, no. 7, March 1966, pp. 237-273.		Reported that in the 1930's in the US three fifths of engineers under 40 were occupied with administrative rather than technical work according to National Science Foundation statistical data
1969	Turner, B. T, *Management Training for Engineers*. London, Business Books			Engineers at English Electric; >50% of work time involved interaction and communication
1970		Heywood, J., Qualities and their assessment in the education of technologists. *International Bulletin of Mechanical Engineering Education*, 9, 15–29		Role analysis of steelworks managers; enabled William Humble of the British Steel Corporation to propose a Taxonomy of Educational Objectives of managers

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	Book	Journal article/ book chapter	Report	
			Venning, M. *Professional Engineers, Scientists and Technologists in the Engineering Industry*, EUITB Research Report no. 4, Watford, Engineering Industry Training Board	Studied around 1000 engineers; noted 52% of work time involved interaction and communication
1983	Hutton, S. P and P. Lawrence *The work of production managers: case Studies at Manufacturing Companies in the United Kingdom*. University of Southampton			Compared German and British production managers
1987	Latour, B., *Science in Action: How to Follow Scientists and Engineers Through Society*. Milton Keynes: Open University Press			Applied Actor Network Theory to the field of Science and Technology Studies
1987		Law, J., Technology and Heterogeneous Engineering: The Case of Portuguese Expansion, in: Bijker, W.E., Hughes, T.P. & Pinch, T.J. (Eds.) *The Social Construction of Technological Systems: New Directions in the Sociology and History of Technology*. Cambridge, MA, MIT Press		Proposed the heterogeneous engineering concept to characterize a proposed network of actors involved in use of maritime technology in the XV century
1991	Sladovich, H., (ed.) (1991) *Engineering as a social enterprise*, National Academy Press, Washington, D.C.			Set out sociotechnical aspects of engineering in the context of the relationship between engineering and society
1994	Gibbons, M., Limoges C., Nowotny H., Schwartzman S., Scott, P & Trow M. *The new production of knowledge: The Dynamics of Science and Research in Contemporary Societies*, Sage Publications, London			Proposed Mode 1 and Mode 2 models to characterize engineering knowledge production in academia and in industry respectively. See Shinn (2002) for a critique of this approach.

YEAR	PUBLICATION			CONTRIBUTION/FINDINGS
	Book	Journal article/ book chapter	Report	
1994	Bucciarelli, L. L. *Designing Engineers*, Cambridge, MA, MIT Press			Suggested that engineering design is a social process that involves constant negotiation among many parties
1996		Etzkowitz, H & Leydesdorff, L. Emergence of a Triple Helix of University-Industry-Government Relations. *Science and Public Policy*, 23, 279–86		Proposed the Triple Helix model of University-Industry-Government Relations. See Shinn (2002) for a critique of this approach.
1996		Vest D., Long M. & Anderson T., Electrical Engineers' Perceptions of Communication Training and Their Recommendations for Curricular Change: Results of a National Survey, *IEEE Transactions On Professional Communication*, Vol. 39, No. 1, March 1996		Study of US-based electrical engineers
1996		Regan, T. M., & Schmidt, J. A. (1999, November). Student learning outcomes: alumni, graduating seniors and incoming freshmen. In Frontiers in Education Conference, 1999. FIE'99. 29th Annual (Vol. 3, pp. 13A5-16). IEEE.		Presented data from alumni studies. There have been a number of such studies (Puerzer & Rooney, 2002; Besterfield-Sacre, M., Shuman, L., Wolfe, H., & McGourty, J., 2000) and in the US they have frequently been employed as an instrument to monitor ABET competence compliance (Passow, H. J., 2012).
1997		Kilduff M., Funk J.L &. Mehra, A. 1997, "Engineering Identity in a Japanese Factory", *Organization Science*, Vol. 8, No. 6, pp. 579-592		Intensive observation of 11 Japanese engineers over an 11-month period.
1998	Downey, G L. 1998. *The machine in me: An anthropologist sits among computer engineers*. New York: Routledge			Looked at engineering practice through an anthropological lens
1999	Rodrigues, M de L., 1999, *Os Engenheiros em Portugal,* Celta Editora, Oeiras			A sociological study, sponsored by the Portuguese Order of Engineers, involving a survey of over 10,000 engineers in Portugal and interviews with 141
2000		Sandberg J. (2000) Understanding human competence at work: an interpretative approach, *Academy of Management Journal,* 2000, vol. 93, N0. 1, 9-25		Noted 3 different conceptions of Volvo engine optimizers and how this affected their work practice
2001	Evans, A. G. T. (2001). *C. Y. O'Connor: His Life and Legacy*, University of Western Australia Press.			Case study of a pioneering engineer in 19^{th} century Australia

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	Book	Journal article/ book chapter		Book
2002	Williams, R., Retooling: *A Historian Confronts Technological Change*. Cambridge, MA, USA, MIT Press			Historical analysis of the evolution of MIT; described the "expansive disintegration" of engineering
2003	Vinck, D. *Everyday Engineering: An Ethnography of Design and Innovation.* Boston, MA, MIT Press			Engineering design seen through an ethnographic lens
2006		Jonassen D.; Strobel J.; Lee C. B., Everyday Problem Solving in Engineering: Lessons for Engineering Educators, *Journal of Engineering Education*; Apr 2006; 95, 2.		Qualitative study of workplace engineering problems identified that workplace problems are ill-structured and complex because they possess conflicting goals, multiple solution methods, non-engineering success standards, non-engineering constraints, unanticipated problems, distributed knowledge, collaborative activity systems
2007	Mukerji, C., *Impossible Engineering: Technology and Territoriality on the Canal du Midi.* Princeton: Princeton University Press			Case study of French engineering in the 17th century
2007		Faulkner, W. Nuts and Bolts and People. *Social Studies of Science,* 37 (3), 331-356.		Study of women in engineering
2009			Frost & Sullivan Whitepaper: *Meetings Around the World II: Charting the Course of Advanced Collaboration,* Frost & Sullivan, Silicon Valley	A global study of business performance concluded that collaboration contributed twice the impact of a company's strategic orientation and more than five times the impact of market and technological turbulence influences. See also Gofus, 2006

YEAR	PUBLICATION			CONTRIBUTION/FINDINGS
	Book	Journal article/ book chapter	Report	
2011		Bailey, D. E. & Barley, S. R., Teaching-Learning Ecologies: Mapping the Environment to Structure *Organization Science,* 22 (1), 262-285.		Presented observational field data showing difference in learning of structural engineers and hardware engineers
2012		Blandin, B. The Competence of an Engineer and how it is Built through an Apprenticeship Program: a Tentative Model. *International Journal of Engineering Education*, 28(1), 57-71. doi: 0949-149X/		Empirical data from a study of apprentice engineers in France whose conclusions support the findings of the Trevelyan research in Australia
2012		Nielsen K. & Heymann M., Winds of change: communication and wind power technology development in Denmark and Germany from 1973 to ca. 1985, *Engineering Studies* Vol. 4, 1		Comparative case study which showed how engineers' communication with the public can influence take- up of new technology. Published in a special issue of Engineering Studies devoted to engineers and communication
2013		Korte, R., & Lin, S. Getting on board: Organizational socialization and the contribution of social capital. *Human relations,* 66(3)		Studied the role of socialization during the initial years of engineering graduates' professional experience
2013			TUEE, 2013, Transforming Undergraduate Education in Engineering, Phase 1 Report, ASEE, 2013	ASEE's Executive Director Norman Fortenberry subsequently called on practicing engineers to engage with faculty on their research activities as this would help academics to "build-in learning experiences to emulate real-world practice" (2014)
2013	Williams B., Figueiredo J. & Trevelyan J. (Eds), *Engineering Practice in a Global Context: Understanding the Technical and the Social*, CRCPress, Taylor & Francis, September			Presented empirical data on the sociotechnical dimension of engineering practice based on studies in 7 countries
2014		Baudrin et al., On n'est pas des cow-boys Controverse sur l'exploitation des gaz de schiste et stratégie de l'industrie pétrolière, *Revue d'anthropologie des connaissances,* 2014/2 Vol. 8, n° 2, p. 451-478. DOI : 10.3917/rac.023.0451		Study of shale-gas exploration policy in a one of two special issues of the Revue d'anthropologie des connaissances devoted to engineering practice
2014		Stevens R., Johri, A. & O'Connor, K. Professional Engineering Work, in In Johri BM & Olds (eds.), Cambridge *Handbook of Engineering Education Research*, Cambridge University Press, 2014, New York, NY		Comprehensive review of engineering practice research

5. Discussion

The timeline in section 5 allows us to identify a number of phases in the evolution of research in the field of inquiry:

The work published early in the 20th century can be seen as having a precursor role in that it focused on improving industrial productivity and did not tend to focus on engineers in particular. The 60s and 70s saw the application of statistical methods to study and categorize the workplace practice of engineers. During the 80s there was an increase in interest in engineering practice by sociologists and the application of actor network theory to describe it. The macro views encapsulated in the Gibbons model and the Triple Helix model of engineering practice and its relation to society, although neither was directly based on empirical data, were widely debated in the 90s.

The 90s also saw an increasing use of alumni surveys as an instrument to measure the match between competences acquired at university and those needed in the workplace. We note an growing use of qualitative methods to gather empirical data relating to engineering design processes and to sociotechnical aspects of engineering; these included methodologies drawn from fields such as organization science, sociology, anthropology and ethnography. This is an important development because the self-reported perceptions of alumni surveys on their own are somewhat limited in their characterization of what goes on in the workplace and the instruments developed by social and organization scientists can provide a considerably richer picture of what engineers do.

6. Implications for Engineering Educators and Trainers

The contours of engineering workplace practice which have been taking shape in the emerging field described in the previous section have implications for engineering education: present courses tend to favour an engineering science approach and do not give attention to the development of competencies that provide value for a firm employing young engineers such as skills in negotiating the socio-technical aspects of workplace practice, effective coordination and communication skills and experience in tackling complex ill-structure problems (Bucciarelli, 2003, Trevelyan 2010, Jorgensen 2007, Korte et al. 2008, Martin 2005).

As Korte and his colleagues have pointed out recent engineering graduates often start with low-level, low-risk assignments which firms described as a method to orient the newcomer to work (Korte et al 2008). Indeed various studies have suggested that novice engineers may take around two years to contribute significant to value to a company[1].

It is now becoming more widely accepted that the engineering workplace typically calls for solutions to "fuzzy" or ill-structured questions (Jonassen et al. al., 2006 p. 146, Nagel et al., 2012) and that these solutions usually involve negotiation with a variety of other actors (Williams & Figueiredo, 2013). Hence, providing contexts for engineering students to develop and practice such skills and for instructors to assess their acquisition is a major challenge facing those involved with engineering education and training today. Furthermore, given recent advances in the areas of IT simulation tools and in augmented computing, it would seem that Bucciarelli's proposals (2003) regarding the harnessing of the power of online technology could

[1] [1] See for example Tilli and Trevelyan (2008): "An underlying assumption that has informed our thinking about engineering work is that training and experience is an essential component of the first few years of an engineering career. This assumption is based on data from the framework study interviews in which all participants said that it took between two and five years for a novice to become 'competent'. While each participant had a different interpretation of competence, all identified this early career period as important";

now be put into effect so as to allow simulation of individual and group role-play activities which would both enable engineering students and trainees to acquire and practice these skills. It would also allow instructors to approximate the kind of performance-based assessment which is increasingly being applied in professions such as medicine and aeronautics but in engineering is still quite rare (Nakamura et al., 2011).

This is very much in line with the proposals in the Phase 1 Report of the Transforming Undergraduate Education in Engineering strategy of the ASEE (ASEE, 2013) as one of the key steps it has identified is "to solicit, distil and share the views of the engineering community (…) with respect to future visions for engineering education appropriate to the full spectrum of challenges and opportunities faced by practicing engineers in a variety of operational contexts" (ASEE, 2013). The authors would suggest that these views would be very much enriched if allied with empirical data on the reality of practicing engineers and that such an evidence-based approach has begun to be feasible. Although such data tend to be dispersed, there are now signs of a growing recognition of the need to bring the empirical data and associated research paradigms together so as to better inform management practice and to contribute to more effective engagement between engineering practitioners and faculty. This would help to address the need identified by ASEE Executive Director Norman Fortenberry to "build-in learning experiences to emulate real-world practice" and would also contribute towards what he identifies as an important takeaway from the Phase 1 Report, namely for "practicing engineers to engage with faculty on their research activities" (Fortenberry, 2014). We would suggest, therefore, that the engagement process would be facilitated by the recognition of engineering practice as a field of research as this has the potential to contribute a solid evidence-based platform for practitioner-educator involvement.

7. Conclusion

In this paper we have used a timeline approach to portray developments in the evolution of engineering practice as an emerging field of study and we note the wide range of research approaches now available to those studying engineering practice. In addition we have pointed out some of the implications for engineering educators and suggested that recent developments in the digital technology could provide the tools for workplace simulation which would emulate the complex decision-making processes which professional engineers routinely face.

The authors believe that by providing a broader perspective on the empirical data which has been accumulating with respect to engineering practice and by showing that there is a growing body of theoretical understanding of such processes that we can contribute to this emerging field and facilitate insights into where future research need to be carried out.

In other words, we hope to have demonstrated in this paper that in the two decades since Vincenti's words at the National Academy of Engineering symposium there has been significant progress in understanding engineering practice, albeit in widely dispersed disciplinary studies, and that this is an emerging area of study which can make an important contribution to decisions about knowledge and skill development of engineering professionals and to the training of future engineers.

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