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DOI:
10.1177/0954405413490160

Citation for published version (Harvard):
Zhang, Y, Gregory, M & Shi, Y 2014, 'Managing global engineering networks part I: Theoretical foundations and the unique nature of engineering', *Proceedings of the Institution of Mechanical Engineers Part B Journal of Engineering Manufacture*, vol. 228, no. 2, pp. 163-171. https://doi.org/10.1177/0954405413490160

Managing Global Engineering Networks (GEN) PART I:

Theoretical foundations and the unique nature of engineering

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Abstract: Network concepts have been widely reported in the current literature on international engineering operations. But a systematic view of the unique nature of engineering is missing and its implications for the design and operations of global engineering networks are poorly understood. This paper seeks to address these knowledge gaps by exploring how leading global companies cope most effectively with the unique nature of engineering in their network operations. A theory building approach based on the case study methods was adopted reflecting the contemporary nature of this study and the complexity of the research object.

The first part of this paper establishes a theoretical foundation for global engineering networks through an analysis of the intrinsic requirements of engineering operations, mapping the influence of the external business environments, and reviewing the relevant engineering network theories and practices. A preliminary framework has been developed to bring together the key issues and provide a foundation for more detailed enquiries/

Keywords: Engineering Management, International Engineering Operations, Global Engineering Networks (GEN)

1. Background and introduction

Network concepts have been studied in international engineering operations as coordination mechanisms [1-2], organization structures [3-4], and industrial practices [5-8]. This is largely driven by the attractions of the network form of organization in offering flexibility [9], reliability [10], cost efficiency [11], and learning ability [12-13]; as well as the demand in engineering operations for effective problem solving [14-16]. Recent developments in engineering networks are converging towards the concept of global engineering networks (GEN) which provide an integrating framework to explain the contextual environments, required capabilities, and enabling configurations of engineering network operations on a global scale [17-20]. However, the existing literature fails to provide satisfactory insights into the difference between GEN and network operations of other functions requirements, including particularly manufacturing [13][21-22] and research [23-25]. The primary concern of engineering differs from the other functions in output, required knowledge and tasks [15][26], and there are serious dangers in adopting network approaches derived from other functions without considering the unique nature of engineering.

We argue through this paper that the effective management of international engineering operations requires a proper understanding of the intrinsic requirements of engineering, including the role of intangible engineering know-how, effective problem solving, adaptation and cross-boundary collaboration, etc. Such characteristics of engineering, combined with challenges from the external business environment, should clearly influence approaches to design and operation of global engineering networks. The focus of the investigation has therefore been: how do leading global companies effectively cope with the unique nature of engineering in their network operations?

The investigation begins by exploring the unique nature of engineering and then introduces the major challenges from current business environments. This provides a preliminary understanding of effective engineering networks from the existing literature, which is then refined and enriched through case studies. The theoretical and practical implications of the key findings are then discussed and directions set for future research.. PART I mainly focuses on identifying the key problems and establishing a theoretical foundation. PART II focuses on introducing the case studies and the key findings.

2. The unique nature of engineering

The term 'engineering' is believed to have originated from the Latin root 'ingeniōsus', meaning ingenious or skilled, and characterised by cleverness or originality of invention, production or construction [27]. The term is now considered broadly as an ability of directing the great sources of power in nature for the use and convenience of humans [28-29], or specifically as activities of finding solutions within constraints of resources, technologies and environments [30-31].

The long history of engineering has been evidenced by great artefacts such as the Sumerians' construction, Egyptian pyramids, Chinese Great Wall, Roman aqueducts or war machinery [28]. Scientific understanding of engineering methods has been dramatically improved since the Industrial Revolution stimulated by the practical achievements of engineers, including the invention and development of steam engines and machine tools for example [29-30]. An historic view of engineering suggests that engineering and science actually stemmed from the same root, while engineering emerged primarily from the work of the inventors and entrepreneurs who paid relatively little attention to the theoretical underpinnings of their technological activities [31-33]. Mitcham (1978:244) in his classification of technologies described such differences like this: *"The [engineering] invention causes things to come into existence from ideas, makes the world conform to thought; whereas science, by deriving ideas from observation, makes thought conform to existence* [34]." A similar attempt by the Royal Academy of Engineering (RAEng 1999:8) began with: "*Engineering research is fundamentally different from curiosity driven basic science research because it is driven by direct relevance to applications for wealth creation and quality of life*….[35]" Lipton more recently in the *Philosophy of Engineering* published by the Royal Academy of Engineering (RAEng 2010:7-13) suggested a set of interesting contrasts between science and engineering by looking into their differences in output, knowledge and drivers [15]. He explained that the philosophy of science concerns the 'light' question, getting to the truth about how the world really works; while the philosophy of engineering concerns the 'fruit' question, the practical task of anticipating and controlling nature[1]. Such differences were also observed in OECD's (Organisation for Economic Co-operation and Development) categorisation of research and development related activities where engineering activities would focus more on the applied research and experimental development than the basic research [36].

These statements indicate that scientists investigate phenomena, whereas engineers create solutions to problems or improve upon existing solutions. To explain phenomena, a scientific investigation may wander at will as unforeseen results suggest new paths to follow, and such investigations never end because they always throw up further questions. On the contrary, engineering is directed towards serving the process of design and manufacturing or constructing particular things whose purpose has been clearly defined. Engineering investigations therefore may end when reaching an adequate solution of a practical problem, or be restarted with renewed interest in or demands upon the product. In this account, engineering has been widely regarded as a process that converts basic science into real societal wealth, i.e. the creative art of using the basic rules of science and the properties of raw materials [31-32][34]. Figure 1 presents an attempt to summarise the above discussions by illustrating the philosophical stance of engineering in contrast to two closely related functional areas, i.e. research and manufacturing.

	Research	**Engineering**	**Manufacturing**
Philosophical Stance	Concerning the truth of how the world works, the 'light' question*	Concerning the underlying truth of the world as a means to the practical use, the 'fruit' question & the underlying 'light' question	Concerning the practical use of a product as well as the production processes, the 'fruit' question
Main Output	Theories, assumptions or hypothesises	Design, solutions or prototypes	Products, artefacts or commodities
Principal Method	Rational reflection or searching for empirical evidence, relying on the knowledge of individual scientists	Interaction with systems through attempts to build, fix or modify them, relying on the know-how of engineers and organisations	Implementation of instructions or procedures in a reliable and efficient way, relying on the expertise of organisations
Drivers for Task Choice	Random problems driven by the curiosity or desire of a scientist	One-off problems given by the customer, colleagues or government	Repetitive tasks co-defined by the customer and the manufacturer

Figure 1. Engineering, research and manufacturing

*Note 1: 'Fruit' and 'light' are the two main aims of classic sciences according to Francis Bacon. 'Fruit' stands for the application of science to enable to anticipate and to control nature. 'Light' stands for understanding how the world works. Referencing from *Philosophy of Engineering* published by the Royal Academy of Engineering in 2010, page 11 [15].

Whilst engineering cannot satisfactorily be captured in a single sentence due to its vast diversity but we have reviewed a number of attempts, ranging from Leonardo Da Vinci's notebooks about 500 years ago to the latest update on Wikipedia (see Table 1).

Table1. Example definitions of engineering

Da Vinci **(the 15th century)**	Engineering is the synthesizing art and technology by embodying the qualities of inquiry, imagination, scientific and technological rigor, vision and creativity- quoted from Hawley (2003:16) [32].
Tredgold **(1828)**	Engineering is the art of directing the great sources of power in nature for the use and convenience of human -quoted from Kirby et al. (1956:2) [28].

Kirby et al. **(1956)**	Engineering is the art of the practical application of scientific and empirical knowledge to the design and production or accomplishment of various sorts of constructive projects, machines, and materials of use or value to man [28].
Rogers **(1983)**	Engineering refers to the practice of organising the design and construction of any artifice which transforms the physical world around us to meet some recognised need [37].
Florman **(1996)**	Engineering is the art or science of making practical application of the knowledge of pure sciences [38].
Jordan et al. **(2002)**	Engineering is the application of science and human experience to solve problems faced by people, which is often done in poorly understood or uncertain situations, using the available resources [39].
Koen **(2003)**	Engineering methods are the strategy for causing the best change in a poorly understood or uncertain situation within the available resources and the use of heuristics [40].
ABET **(2004)**	Engineering is the profession in which a knowledge of the mathematical and natural sciences, gained by study, experience, and practice is applied with judgment to develop ways to utilise, economically, the materials and forces of nature for the benefit of mankind [41].
Dictionary.com **(2005)**	Engineering is the application of the scientific and mathematical principles to practical ends, e.g. design, manufacturing, and operation of efficient and economical structures, machines, processes, and systems. It means the application of science, accomplished by applying the knowledge, mathematic, and practical experience to the design of useful objects or processes, to the needs of humanity [42].
Encyclopaedia Britannica **(2007)**	[Engineering is] the application of science to the optimum conversion of the resources of nature to the uses of humankind [..] the creative application of scientific principles to design or develop structures, machines, apparatus, or manufacturing processes, or work utilising them single or in combination; or to construct or operate the same with full cognizance of their design; or to forecast their behaviour under specific operating conditions; all as respects and intended function, economics of operation and safety to life and property [43].
Merriam-Webster **(2007)**	[Engineering is] the activities or function of an engineer, i.e. the application of science and mathematics by which the properties of matter and the sources of energy in nature are made useful to people, or the design and manufacture of complex products [44].
Wikipedia **(2011)**	Engineering is the discipline, art, skill and profession of acquiring and applying scientific, mathematical, economic, social, and practical knowledge, in order to design and build structures, machines, devices, systems, materials and processes [45].

These definitions collectively suggest the unique nature of engineering as follows:

- **Relying on intangible engineering knowledge**. The working approach of engineering involves scientific rigor, and equally importantly, engineering creativity. Engineering know-how, e.g. the skills, expertise and experience of engineers, has always been a critical element in novel engineering solutions. Such knowledge is a matter of having some abilities which do not necessarily exist in the form of beliefs that an engineer can articulate or write down and pass on. For this reason, engineering methods sometimes require approximation to accommodate such intangible engineering knowledge, e.g. the Navier-Stokes equations to solve aerodynamic flow over an aircraft or Miner's rule to calculate fatigue damage [46].

- **Emphasising effective problem solving**, i.e. valuing the practical use of engineering outputs. Engineering is concerned mainly with developing and exploiting knowledge for the innovative design of products and systems for the convenience and benefit of human beings. Engineers emphasise the practical value and usefulness of their work, and therefore seek for effective problem solving in various situations. The importance of practical value was highlighted in the statement of NAE (2004) as engineering's ultimate mission to maintain the nation's economic competitiveness and to improve the quality of life for people around the world [26].
- **Requiring adaptation and quick response** in uncertain working environments. Major drivers for engineering task choice are external, e.g. the customer, colleagues, or governments, rather than solely based on the curiosity of an engineer or driven by an engineering organisation's desire for discovery [15]. At the same time, engineering tasks are often one-off problems. It therefore is difficult to specify such tasks comprehensively and precisely at the outset of a complex engineering project. To solve unpredictable engineering problems with limited resources and limited time available, engineers have to adapt their working methods effectively and respond quickly to changing contexts.
- **Requiring cross-boundary collaboration.** Engineering activities need to identify, understand and integrate constraints on a design in order to achieve a successful result. An actual engineering task is often complex and unpredictable, and in most cases the required knowledge is possessed by an organisation (rather than an individual), shared by the members and stored in records or on databases. To produce a useful solution in an effective manner, engineering processes increasingly depend on inputs from different technological disciplines or multiple organizations. Cross-boundary collaborations are therefore essential for contemporary engineers to acquire knowledge for the specific task of designing new systems for challenging applications [35].

Driven by the above characteristics, the primary concern of engineering therefore differs from that of manufacturing or basic research in the tasks, outputs and required knowledge. The main drivers for engineering task choice are often external sources rather than the curiosity of an engineer or the scientific desire of an engineering organisation [15][26]. The outputs are often one-off designs or solutions for the benefit or convenience of people, rather than standardised manufacturing outputs [92], or a scientific enquiry or theory purely to improve our understanding of the world or to fulfil the discovery desire of a researcher. The required knowledge, especially engineering know-how, is often intangible and embedded in different parts of an organization or a group of organizations [14][17]. Such intangible, practical, unpredictable and embedded characteristics of engineering will heavily influence approaches to managing international engineering operations.

3. External environments of engineering operations

Engineering management has been generally referred to as the use of engineering processes to enable the creation of knowledge, products, services and markets [47], or specifically defined as the process of envisioning, designing, developing, and supporting new products and services to a set of requirements, within budget, and to a schedule with acceptable levels of risk [48]. Engineering operations have to rely on internal management systems to address these intrinsic requirements, as well as coping with demands from the external business environments [3][49].

The recent trends of globalisation have brought companies opportunities in supporting global markets, accessing global resources, gaining operational efficiency, and developing strategic capabilities [50-51]. Engineering operations are more likely to be dispersed because (i) companies increasingly move towards smaller and decentralized units that suit the complex and information-rich characteristics of engineering [6]; (ii) specialized engineering skills and talents often locate or develop locally so managers disperse their engineering units to access such knowledge and skills [14]; (iii) improvements in education in developing countries, the expansion of large engineering firms to emerging economies and the advent of communication technologies has led to the increased trade in all disciplines of engineering activities worldwide [52]. These driving forces have led to major changes in current engineering operations in two main areas. One is the pursuit of efficiency via the specialization of engineering capabilities: engineering resources have been concentrated to organizational units best suited to the business environments [9]; and the other is the pursuit of effectiveness via internal resource allocation based on returns: engineering resources are largely directed by business plans and market opportunities [18][53]. These changes have increased the interdependency between functionally and geographically dispersed engineering resources, thus increasing the complexity and uncertainty in international engineering operations. The main trends of developments leading to a changing global landscape of engineering include:

- **Changing role of engineering operations.** Some traditional engineering sectors have been shifting away from the developed economies to lower-cost locations or emerging economies [52]. Many companies in the developed countries are now trying to transform their home operations towards a knowledge-based model which requires engineering skills and expertise to play a driving role in delivering customer value rather than simply supporting manufacturing activities [54]. Ongoing developments include the emergence of the advanced manufacturing sectors [55], the increase of engineering services in the traditional manufacturing sectors [52], and the transformation towards sustainable industrial systems [56][96].

- **Engineering outsourcing and engineering off-shoring.** Another significant trend is that many engineering companies in developed countries are now trying to focus on higher value-added operations and outsource low value operations through global supply networks [57]. However, engineering capabilities are often dispersed across different parts of their businesses and deeply embedded in one organisation or a group of organisations. This has made outsourcing decisions especially complex and difficult in engineering operations. For example, after cross-border mergers and acquisitions (M&A), engineering resources can be very difficult to move from one place to another without losing capabilities [58]. A closely related trend is engineering off-shoring which becomes a popular solution to deal with shrinking engineering resources in the developed countries or to benefit from increasing engineering capabilities overseas [8][20][52]. This allows companies to take advantage of low cost resources in the short term, but such decisions will have far-reaching and complex consequences in their engineering operations [14][59].

- **Rapidly changing markets, emerging technologies and new concepts of operations.** Rapidly changing markets and emerging technologies bring new business processes and novel concepts of operations which can be radically different from the traditional ways of managing engineering activities. To deal with the accelerated pace of technology exploitation and the demand for changes in implementation, managers typically have to update their engineering decision making to be more dynamic and proactive [60]. This often leads to a changes of business model with various initiatives and subsequent changes of engineering operations, especially in restructuring programmes towards more sustainable industrial systems [96], or in continuous improvement programmes towards lean or agile enterprises [48][61].

4. Studies on engineering networks

Network based organisation structures, coordination mechanisms, and practices have been developed to address the above challenges. The relevant studies were reviewed by Zhang et al. in 2006 [19] and 2007 [17] with the three main categories as below.

- **Network Coordination Mechanisms** as the third form of organisation coordination [62-63] after the traditional *market* mechanism and the *hierarchy* [10][65][68-69]. Such organisations are characterised by horizontal patterns of exchange, interdependent flows of resources, and reciprocal lines of communication [64-66]. Network organisations and their members often demonstrate collective learning ability to achieve some strategic objectives through accessing and deploying dispersed resources [63][67][70].
- **Network Organisation Structures,** especially the matrix of the *functional* approach and the *project* approach to engineering management [3][71]. Matrix organisations can be organised by dimensions of product categories, technology disciplines, geography regions, or management functions. Such structures provide adaptability and flexibility in deploying resources and allow the long term development of expertise within disciplinary or technological domains [72-73]. This however requires effective coordination and conflict management between different matrix dimensions [74].
- **Engineering Network Practices,** including the introduction of global product development processes [75], the development of concurrent/simultaneous engineering [76-78] and collaborative engineering [79-80], as well as the use of virtual teams [87-90] and centres of excellence [91]. An important development in this area is the product lifecycle management (PLM) as an integrated system for managing product related activities throughout the lifecycle [81-83]. PLM applications have recently been extended from new product development activities to include a broader scope of collaboration and integration activities, e.g. supply chain integration [84], project management [85], through-life support and maintenance [86], and manufacturing knowledge sharing [97].

The concept of global engineering networks (GEN) has been proposed to integrate the above developments of engineering network theories and practices. Zhang *et al*. (2008) revealed the evolutionary trends towards GEN by investigating the major drivers, main barriers, organisational features, and performance preferences [18]. Zhang *et al*. (2007) proposed an overall framework for understanding GEN through investigating their contextual features, critical capabilities to compete in particular contextual circumstances, and configuration characteristics to deliver the capabilities [17]. Based on strategic management theories and the operations management literature, especially the contingency theories [93], the configuration theories [94], and the theories of organizational or operational capabilities [21][95], the GEN framework suggests a configuration view to systematically describe the organisational features of engineering network operations from the perspectives of network structures, operations processes, governance systems, support infrastructure, and external relationships [16].

5. Towards a theoretical foundation for effective engineering networks

Table 2 summarizes the key issues addressed by the engineering network studies and indicates their linkage to the unique nature of engineering. Above all, many companies are expected to manage their engineering operations on a global scale, including the organization of global engineering resources and the coordination of global engineering activities. This addresses the need of engineering operations for effective collaboration across disciplinary, geographic and organisational boundaries; and helps companies to cope with challenges in engineering off-shoring and outsourcing decisions in a strategic manner. At the same time, companies have to effectively use both their explicit engineering knowledge and their tacit engineering know-how and expertise. Improving knowledge-sharing between globally distributed engineering teams is a key task. This reflects the heavy reliance of engineering on the skills and experience of engineers and helps to maintain the core engineering capabilities of a company. In addition, companies should successfully exploit their networked engineering capabilities via appropriate network coordination mechanisms and network structures. This reflects engineering's emphasis on effective problem solving, and allows companies to build adaptable network capabilities in rapidly changing business environments. Last but not least, companies should support their international engineering operations through integrated information and communication technologies (ICT), e.g. integrated ICT tools, processes, and infrastructure. This facilitates knowledge-sharing and effective collaboration, and provides potential directions for developing novel business models and innovative concepts of operations.

Table 2. Key issues addressed by the engineering network studies

		Global Engineering Operations	**Engineering Knowledge Management**	**Exploitation of Network Capabilities**	**Integration of Information and Communication Technologies (ICT)**
Engineering Networks	Network Coordination Mechanisms	Synergies of globally distributed engineering activities	Allowing freer and thicker information flows	Enabling efficient transactions; flexible and reliable relationships	Introducing ICT enabled and integrated processes
	Network Organisation Structures	Linking globally dispersed engineering resources	Developing expertise within functions and share expertise across	Allowing flexible combinations of engineering resources	Providing ICT tools and infrastructures

			projects		
	Engineering Network Practices	Globally dispersed and interdependent engineering teams	Improving explicit engineering knowledge transfer and tacit engineering knowledge sharing via formal or informal mechanisms	Benefiting from a certain scale of operations and allowing quick response to changes	Introducing ICT based engineering solutions or initiatives, e.g. product lifecycle management systems, engineering knowledge database, etc.
Relevance to the External Business Environments		Engineering off-shoring and outsourcing decisions	Maintaining and developing core engineering expertise as a main source of competitiveness	Building adaptable engineering network capabilities in rapidly changing business environments.	Providing potential directions for developing novel business models and innovative concepts of operations
Linkage to the Unique Nature of Engineering		Enabling collaboration across disciplinary, geographic and organisation boundaries	Managing intangible engineering knowledge, especially in key capability areas	Emphasising effective problem solving; solution-driven working approaches in uncertain environments	Facilitating knowledge sharing and effective collaboration

Figure 2 summarises the above review and illustrates the rationale of theoretical development through case studies which will be introduced in detail in Part II of this paper. In brief, the unique nature of engineering, together with the requirements from the external business environments, will influence the way of managing international engineering operations. Network concepts have been developed to address the challenges in current engineering operations. The recent developments have been integrated into the concept of global engineering networks (GEN). Our investigations were focused on understanding the essential elements of effective engineering networks which would characterise GEN from network operations with other functional requirements.

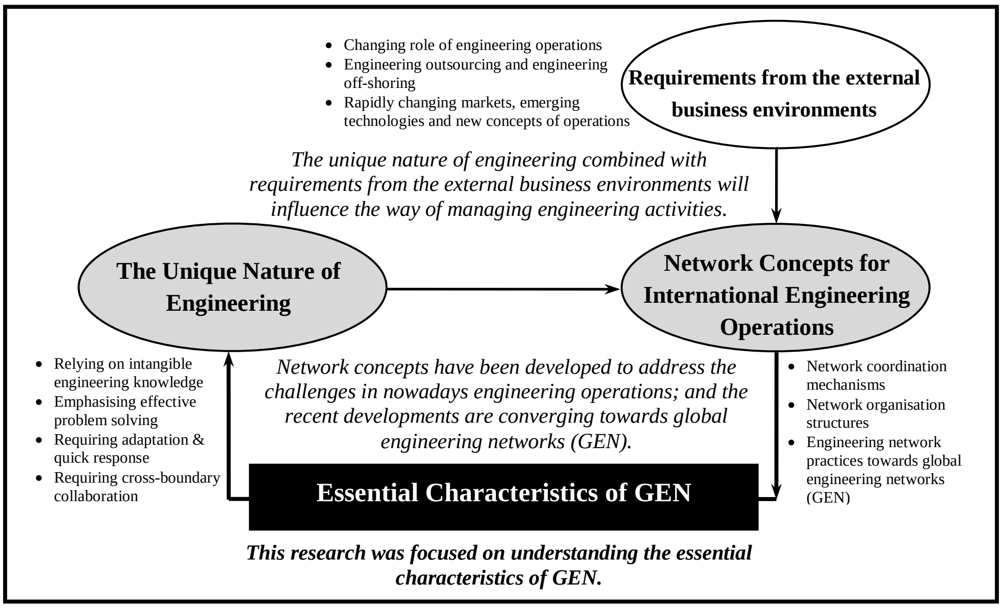

Figure 2.Towards a theoretical foundation for effective engineering networks

Acknowledgement:

This study at its later stages of validation and integration has been supported by the Seventh Framework Programme of the European Union through Marie Curie Actions IRSES Europe-China High Value Engineering Network (EC-HVEN). Grant No. EC FP7 PIRSES-GA-2011-295130.

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