Management Engineering: The Engineering of Management Systems

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Abstract

This paper presents an overview of the emerging discipline of management engineering. Management engineering deals with the application of engineering theory and methods to the design, planning and operation of management systems – that is, the engineering of management systems. Management systems are socio-technical in nature, combining people, materials, information and technology. Management engineering can be viewed as a contemporary form of industrial engineering (IE), which reflects the increasingly technical nature of management and organizational processes due to the use of information technology, and the extension of analytical methods used by IEs in manufacturing and process industries to applications in a wide variety of other public and private sector domains. The University of Waterloo is the first Canadian engineering school to offer a dedicated undergraduate program in management engineering, with a curriculum that integrates analytical methods taught in traditional IE programs, information technology topics from software engineering and computer science, and social science topics dealing with the behavioural and economic characteristics of management systems. Similarities and differences between management engineering and the two related disciplines of industrial engineering and engineering management are discussed. Two management engineering case studies are presented, describing analytical methods and information technologies used in surgical scheduling and computational advertising. The paper concludes with a discussion of certain issues and challenges facing management engineering educators, researchers, and practitioners as they develop the institutional frameworks needed to support and legitimize professional engineering practice in the domain of management systems.

Introduction

Management engineering is an emerging discipline concerned with the design, planning, and operation of management systems, comprised of people, materials, information, and technology. In other words, management engineering deals with the engineering of management systems. Management engineers apply analytical methods such as optimization, statistical analysis, and computer simulation, to model and design management decision processes, systems of information and material flow, work operations, and logistical supply chains. They develop and use databases, decision support systems, telecommunications, and other computing and information technologies, to improve business decision making, organizational communication, and business information processing. Management engineers combine expertise in analytical methods and information technology with knowledge of social and economic processes to design integrated management systems that serve organizational needs.

This paper begins with an overview of the historic emergence of management engineering as a discipline. We then describe the University of Waterloo's new undergraduate program in management engineering, followed by a discussion of similarities and differences between management engineering and other established disciplines. Next, we present two management engineering case studies along with other application examples. The paper ends with a discussion of certain issues and challenges facing management engineering as an emerging discipline.

Background

Management engineering can be viewed as a contemporary form of industrial engineering. Its emergence as a discipline reflects the evolution of industrial engineering practice to address two significant trends: (1) the increasingly technical nature of management and business processes due to the pervasive use of information systems and technology in modern organizations; and (2) the extension of industrial engineering methods beyond traditional manufacturing and process industries, to applications in a diverse variety of other public and private sector settings, including health care, financial services, energy, telecommunications, transportation and logistics, supply chain operations and retail.

Industrial engineering was initially established as a discipline that focused on the design and study of work processes. It grew out of the industrial age almost one hundred years ago, and was popularized by the pioneers Frederick Taylor and Frank and Lilian Gilbreth whose interests were in the design of methods to increase factory worker productivity. At the time, manufacturing and process industries were the mainstay of North American economic growth, and improving the efficiency of factory work was key to sustaining this growth. As time passed, the tools that industrial engineers used evolved; time and motion studies and scientific management methods gave way to the use of mathematics of optimization to develop models for efficient production and distribution systems. Others began to look at human and labour relations as well as the ergonomics of the human-machine interface.

As the tools industrial engineers employed evolved, so did the workplace. Over the course of the last half century, there has been a tremendous shift in economic activity and society.

Manufacturing is no longer the driving force for the Canadian and North American economy it once was. Growth in the service sector and the rapid expansion of information technologies have given rise to work and work processes that are fundamentally different from those of one hundred years ago. While industrial engineering was largely the domain of mechanical engineers with management interests then, today, knowledge of software, computer and telecommunications technologies is key to understanding how we can make the modern workplace productive and efficient. Today, we must understand how technology pervades the workplace and its impact on human endeavours if we are to design effective management systems. Management engineering combines the analytical methods of industrial engineering, the information technology knowledge of software engineering and computer science, and social scientific knowledge of organizations and management systems, to address the fundamental shifts that have taken place in the workplace in a post-industrial era.

The University of Waterloo Management Engineering program

The University of Waterloo is currently the only Canadian engineering school to offer an undergraduate degree program in management engineering. The program was launched in 2007 and graduated its first class of management engineers in 2012. It is a co-operative education program, consisting of eight four-month academic terms and six four-month co-operative work terms, for a total duration of four and two-thirds years. The program is administered within the Faculty of Engineering by the Department of Management Sciences, which has offered an Option in Management Sciences to undergraduate engineering students for several decades, as well as graduate programs at the Master's and Ph.D. levels. The management engineering program was accredited by the Canadian Engineering Accreditation Board in 2012.

The program develops student competence in four general areas:

1. *Foundational knowledge in mathematics, basic science, and engineering sciences.* During the first two years, students take foundational courses in algebra, calculus, numerical methods, probability and statistics, physics, chemistry, electricity, material science, solid mechanics, and thermodynamics.

2. *Analytical skills to structure, model, and solve management engineering problems.* The curriculum builds analytical skills through core and elective courses that share much in common with traditional industrial engineering programs. The core program provides analytical training in linear optimization, deterministic optimization, stochastic models, and simulation analysis and design, and introduces students to problems in key application domains of work analysis and facilities planning, operations planning and inventory control, and supply chain management. Elective courses provide opportunities for students to develop advanced analytical skills in decision analysis, deterministic and stochastic optimization, and to study various application domains of interest, including quality management and control, scheduling, and other management engineering applications.

3. *Technical computing skills to design and develop information technology solutions that improve business operations and management processes.* The curriculum develops skills

in information systems and computing through core courses and technical electives that reflect important advances in the application of information technology to the design and operation of management systems. Core courses include programming, algorithms and data structures, database systems, software engineering methods, information systems analysis and design, and telecommunications systems. Electives include courses in human computer interaction, data warehousing and data mining, decision support systems, and information retrieval. The subject matter of these courses draws heavily on disciplines such as software engineering and computer science, but teaching within management engineering emphasizes the application of information technology to solve technical management and organizational problems, rather than problems primarily associated with the computational technology itself.

4. *Contextual knowledge to understand the economic and organizational settings in which management engineering solutions are implemented.* Complementary studies courses are integrated in the core program, introducing students to the economic, organizational, and socio-technical context of management engineering applications. Students take core courses on professional engineering concepts, engineering economics, managerial economics, managerial and cost accounting, organizational behaviour, and organization design. To enhance student understanding of management engineering contexts further, elective courses are available in the strategic management of technology, entrepreneurship, new product and process innovation, the economic impact of technology, and the impact of information technology on organizations and society.

Integration of these different curriculum areas was an important goal in the design of the Waterloo management engineering program. The program was designed to give students sufficient depth in each area to tackle challenging technical problems with confidence, while also providing them with a diversity of intellectual perspectives to appreciate the complex and multi-faceted nature of management systems. To support these objectives, many courses from these different areas are taught by faculty members from within the Department of Management Sciences, rather than several different university departments. The department faculty complement includes individuals trained in industrial, mechanical, electrical and systems engineering, operations research, information and computer sciences, management science, economics, and psychology, including several with training in two or more academic disciplines. A high degree of faculty diversity within a single engineering department creates exceptional opportunities for coordination between course instructors and for intellectual collaboration across academic disciplines.

Management engineering students can add further depth and breadth to their engineering training by choosing upper year technical electives from other Waterloo engineering departments, such as civil engineering courses on transportation systems, or mechanical engineering courses on manufacturing processes. This elective structure is designed to provide management engineering students with insights into the knowledge frameworks of other engineering disciplines, enabling effective collaboration with other professionals in their future careers.

The Waterloo management engineering program differs from most other university programs that combine management and engineering in various ways. For example, in many schools students can take management courses as a supplement to their engineering degree (e.g., combined engineering/MBA programs, BEng with a minor in business/commerce, etc.), or postgraduate training in engineering management. In the Waterloo program, management systems are not viewed as separate from the activity of engineering, but as the problem domain to which engineering methods are applied. That is, the focus is on the *engineering of management* systems, not the management of engineering or a combination of engineering plus management.

Although management engineering is a new program at the University of Waterloo, there is growing evidence of strong market demand for its students and graduates. Management engineering students have enjoyed high co-op work term placement rates and a wide diversity of employers and jobs. They have been employed in private and public organizations in virtually all major sectors of the economy, including computing and information technology, telecommunications, consulting, banking and financial services, manufacturing, food and beverage, retail, health care, energy, construction, transportation and logistics, military, government, and education. They have worked for both established organizations and entrepreneurial start-ups. Co-op jobs have included the modeling, analysis, and design of business and management systems, software development, manufacturing process design, project management, team supervision and various other roles. Graduates of the management engineering program have pursued a diverse variety of career paths, including graduate school, starting entrepreneurial ventures, or finding employment in consulting, modeling and analysis, software applications development, manufacturing engineering, and project management.

Comparison between Management Engineering and Other Disciplines

Overall, the University of Waterloo program develops a body of technical knowledge and skills distinct from both traditional industrial engineering and computer/software engineering, and the term "management engineering" was chosen to reflect these differences. Although Waterloo offers the only dedicated management engineering program in Canada, other Canadian and international engineering schools provide training on topics related to management engineering, and many of their graduates solve management engineering problems in their professional careers. Below we discuss similarities and differences between the University of Waterloo's management engineering program and the two established disciplines of industrial engineering and engineering management.

Industrial Engineering

Industrial engineering is the traditional academic discipline most closely related to management engineering. There are currently nine CEAB accredited undergraduate programs in industrial engineering or closely related fields in Canada (see Table 1) and over ninety ABET accredited IE programs in the US (http://www.abet.org/). As discussed, management engineering can be viewed as a contemporary form of industrial engineering and the two share common analytical methodologies of mathematical optimization, computer simulation, probability and statistical analysis. However, management engineering considers a broader range of problem domains than traditional industrial engineering programs, provides greater technical depth in computing and information systems, and integrates social science training relevant to the analysis of management systems.

Industrial engineering historically focused on problems of operational quality and efficiency in manufacturing and process industries. However, with the North American decline of these industries in recent decades industrial engineers have increasingly applied their analytical methods in non-traditional private and public sector domains, including settings like healthcare where the term "industrial" seems out of place to practitioners. Consequently, many engineering schools have attempted to rebrand their IE programs in ways that emphasize generic IE methods and problem solving approaches, rather than affiliations with any particular industry sectors. Although manufacturing and process industry applications remain the central focus of most IE programs, a growing number of schools have begun to define themselves more broadly, in ways that are similar to how we conceive of management engineering.

Management engineering also includes considerably more technical training of software and computing topics than typical industrial engineering programs, reflecting the increased importance of information technology in management and business operations. Only a small number of Canadian and US IE programs include substantial depth in IT topics such as data structures and database systems, algorithm design, software engineering methods, system analysis, and telecommunications. The University of Toronto's industrial engineering program (www.utoronto.ca) and Rensselaer Polytechic Institute's industrial and management engineering program (http://ise.rpi.edu/) are examples of IE programs that provide technical IT training at a depth comparable to that of the University of Waterloo's management engineering program. On the other hand, the majority of IE programs provide relatively little core IT training beyond an introductory computer programming course. Students in most IE programs who wish to acquire sufficient technical knowledge to tackle challenging IT-based management engineering problems must seek IT electives outside of their core program.

Finally, management engineering includes consideration of non-technical aspects of management systems, such as the social science of human behaviour, decision-making, organizational design, and microeconomics, to help students understand the socio-technical context and behavioural dimensions of management engineering problems. In many IE programs, training related to social and behavioural aspects of work systems focuses quite narrowly on topics like the time and motion analysis of physical work, the ergonomics of workstation design, or the engineering economics of cost-benefit analysis. Although accredited IE programs include some social science content to satisfy CEAB or ABET requirements, this is often done through supplementary elective courses that are not well-integrated in the core curriculum. We would argue that an effective management engineering education requires an integrated treatment of relevant social science topics, to provide students with a holistic understanding of both social and technical characteristics of management systems. Some IE schools offer such an integrated approach, but many provide a more limited analysis of human behaviour.

In summary, many IE programs continue to identify primarily with manufacturing and process industries and provide relatively little training in IT and social science topics. Such traditional IE programs share analytical methodologies with management engineering, but they are otherwise quite different. A small number of IE programs have recently implemented curricula more similar to management engineering, by broadening their focus beyond manufacturing, providing substantial depth in IT topics, and integrating social science training related to behavioural aspects of management systems.

Table 1: CEAB Accredited Programs in Management Engineering, Industrial Engineering, and related fields

School	Program	Accredited since*	Website
Concordia University	Industrial Engineering	1995	www.concordia.ca
Dalhousie University	Industrial Engineering	1969	www.dal.ca
École Polytechnique de Montreal	Génie industriel	1973	www.polymtl.ca
École de technologie supérieure	Génie des opérations et de la logistique	2008	www.etsmtl.ca
University of Regina	Industrial Systems Engineering	1984	www.regina.ca
Ryerson University	Industrial Engineering	1992	www.ryerson.ca
Université du Québec à Trois Rivières	Génie industriel	1980	www.uqtr.ca
University of Toronto	Industrial Engineering	1965	www.utoronto.ca
University of Windsor	Industrial and Manufacturing Systems Engineering	1974	www.uwindsor.ca

*Source: www.engineerscanada.ca

Engineering Management

University programs in engineering management also overlap to some extent with management engineering, but the two disciplines are quite distinct. The essential difference is that engineering management emphasizes the management of engineering, whereas management engineering deals with the engineering of management systems. More specifically, most engineering management degrees are post-graduate programs aimed at engineers from various disciplines who are advancing in their careers into technical management or supervisory roles. These programs help engineers develop the management skills needed to supervise other engineers, manage an organization's engineering function, or manage large engineering projects. For example, they teach skills related to project management, interpersonal and communication skills as well as integrative and interdisciplinary skills in marketing and economics (Lannes, 2001). By contrast, management engineering is concerned with use of engineering theory and methods to design, plan, and improve the operation of management systems, comprising people, materials, information, and technology. The focus is on making management processes and decision-making in the workplace efficient and productive, not the skills needed to be a practicing manager.

Besides post-graduate programs, some universities offer undergraduate degrees in engineering management, including eleven ABET-accredited programs in the US (http://www.abet.org/). Typically these include a technical core of engineering science and design courses, supplemented by various business management courses on technology strategy, project management, organization design, accounting, human resource management, and related topics. Many are structured as generalist engineering degrees, where the technical core includes a mix of core and elective courses from different engineering disciplines. For instance, one student might choose technical courses in civil engineering to prepare for a career in construction project management, while another might choose electrical engineering courses to prepare for a technology management career in the electronics industry. Some engineering management programs provide a technical core similar to industrial engineering, including topics like optimization, work analysis, and computer simulation, although these are typically covered in less depth than one would find in IE programs. Compared to management engineering, undergraduate engineering management programs provide similar coverage of non-technical topics in business and management, but less technical depth in analytical methods, and relatively little coverage of software, computing and information technology topics.

Management Engineering Applications

Management engineers are trained to work on a wealth of applications with a variety of organizations. They are equipped to analyze decision processes within an organization and to seek ways to improve them. Transforming data into actionable insights, optimizing a system with respect to a given measure, or solving socio-technical problems due to technology implementation, are broad areas that could benefit from management engineers.

As a contemporary form of industrial engineering, all traditional IE application domains are open to management engineers. These include manufacturing related areas, production planning and scheduling, motion and time study, work design areas, ergonomics, as well operations management and operations research. Given advances in technology and the IT focus of their training, management engineers are equipped with better tools to tackle such problems.

Management engineers work and consult in virtually every other industry as well, including communications, transportation, retail and energy distribution, banks and insurance companies, hospitals and healthcare organizations, and entertainment firms. Business success is highly dependent on making the right operational and strategic decisions, with information being the key component in making the right choice. This is not new, but in today's highly digitized world, massive amounts of data are now available, which can be transformed to valuable information to improve the quality of management decision making. Financial, sales volume, and environmental transactions are just a few examples of data that can be exploited to improve business processes. "Business analytics" (Davenport & Harris, 2007) is a newly coined term that refers to the use of quantitative tools and methods to dig into past data and provide insights, trends, and patterns to help with decision making. The techniques it applies are at the heart of management engineering, including statistics, operations research, optimization, simulation, and database systems, as well as emerging methods in pattern recognition, data mining, and information storage and retrieval. Management engineers are trained to design and implement IT-based decision support systems that apply analytical and data management techniques in diverse management domains. Researchers are actively exploring these topics both theoretically and practically. For example, healthcare is an application area that has recently benefited from this activity, with studies on all aspects of the healthcare system using data mining, optimization, simulation, and statistical techniques, to name a few[1].

[1] For example, see the newly established journal *Operations Research for Healthcare*, Elsevier 2012.

Management engineers are also well-equipped to handle problems related to the management of technology in organizations. With a foundation in accounting, finance, economics, organizational behavior and organizational design, they are able to analyze socio-technical systems to identify and deal with operational and organizational issues related to managing innovation and technological change. Furthermore, they are qualified to work on interdisciplinary teams that require both engineering and management expertise, to manage technical functions in almost any enterprise, or to undertake the management of broader functions in a high-technology enterprise.

Following are examples of co-op work term projects that have been undertaken by University of Waterloo management engineering students (employer and job specifics have been disguised)[2].

1. *Survey design and process optimization.* A management engineering student studied and analyzed check-in kiosks used by a major Canadian airline. Approximately 70,000 observations were made during six weeks of data collection. Based on the data, reliable estimates for important efficiency indicators, such as wait time, transaction time, and availability of assistance, were calculated and documented.

2. *Software redesign and implementation.* A charter company's outdated booking application software was redesigned to store, email and print booking forms, and to interface directly with accounting and other business applications. After implementation, the system was checked on a daily basis to ensure functionality.

3. *Construction cost estimation.* Costs were estimated for three major construction projects based on building layouts and material requirements. Standard industry pricing sources and measurement instruments were used to estimate the quantity and pricing of various construction materials.

4. *Manufacturing layout design and quality assurance.* An analysis of quality assurance tasks was conducted for a major textile manufacturer. It was determined that greater efficiency could be achieved by re-arranging the placement of testing apparatus based on human factor concepts. A new layout design was proposed and implemented.

5. *Municipal road maintenance efficiency improvement.* A winter severity index was developed to guide road salt usage in a municipality. Winter severity was modelled and tested using three-year historic data on the proportion of bare pavement (road segments that are not covered with snow or ice), relative to the total number of bare pavement days per year. The index was found to generate a 3-5% reduction in annual salt usage.

6. *Information technology/inventory management.* For a software component company, a management engineering student discovered that about 30% of problem reporting tickets contained mistakes in listing configuration details, which resulted in purchasing the wrong computer components and providing mismatched software patches to internal clients. The student generated a list of selection criteria based on communication with internal teams and external vendors and a new ticket inventory system was implemented based on the recommendations.

[2] We thank Ada Hurst for assistance in preparing this list.

7. *Production efficiency and productivity analysis.* A three-month study of a manufacturer's assembly line efficiency and productivity was conducted, including 20 operations from 20 workstations across 15 product lines. The results were used to assess the firm's production capability for expansion into new Original Equipment Manufacturer (OEM) product markets.

8. *Hospital infrastructure improvement.* A management engineering student contributed to numerous hospital infrastructure improvement projects, gathering requirements, estimating costs, and preparing funding applications. The most notable project was a clinical renovation with the objective to bring in more clinical staff and improve patient safety by designing a new floor layout and installing security cameras in sensitive areas such as the trauma floor.

9. *Manufacturing process improvement.* A student designed a paint recovery system and implemented several other process improvement projects to reduce cycle time and improve efficiency at a major automotive manufacturer. The work involved collecting and analyzing process data, designing new processes, procuring new equipment, supervising internal work crews and external contractors, and implementing the proposed solutions.

10. *Retail inventory management.* An analysis of shipment data was completed for a major consumer goods distributor. Based on the results, she worked with suppliers, merchandising teams, and internal stakeholders to reduce lead-time and optimize inventory levels to maintain high retail service levels during the Christmas holiday season.

11. *Financial securities decision modeling.* Statistical interest rate models and an analysis of yield curves were used to develop improved decision support tools for securities traders working on the trading floor at a major investment bank.

12. *Strategic military decision modeling.* A genetic algorithm was developed to support strategic military decision making and a computer based decision support system was implemented to help decide which military aircraft to send on defense missions.

13. *Software development for municipal planning operations.* A client application was developed for a mid-sized Canadian city to manage the maintenance schedules and costs of all property assets. Another application was developed to manage property acquisition projects for road expansions.

14. *Pharmaceutical demand forecasting.* A user-friendly spreadsheet forecasting tool was designed to predict demand for a pharmaceutical firm's cancer drug, based on an analysis of historical data and published chemo regimen monographs.

Following are more detailed case studies describing two technical problem domains within the scope of management engineering: surgical scheduling in hospitals, and computational advertising.

Case Study: Master Surgical Schedules

Technological advances, demand for high-quality health care and an ageing population have created mounting pressure on hospitals and other healthcare providers to afford timely access to a host of healthcare services. Surgical services are no exception as witnessed by growing concerns about lengthy wait-lists and mounting public debate over the costs and social implications of private surgical services in Canada or across the border in the US.

While the issue of managing wait-lists is highly complex, at the core of the resource balancing act are hospitals and hospital operating rooms. Efficient use of OR capacity is well understood to be an important piece in the overall puzzle of providing timely care. As a result, planning and scheduling of operating rooms has been the focus of many practitioner and researcher studies aimed at getting the most productive use from capital intensive resources. While optimal OR room schedules are desirable, limiting the scope of such studies to a single department can produce sub-optimal results. Operating room activities have such a large impact on the workload of many other departments within a hospital that ignoring these interactions can create unanticipated workload fluctuations that erode gains made by “optimal” OR schedules. In particular, bed management for post-surgery patient recovery has proven to be one of the biggest concerns, as downstream blockages in patient flows can result in cancelling surgeries, an undesirable outcome for both the patient and the hospital.

Creating a surgical schedule has classically taken place in three stages: (1) long term allocation of OR time to each surgical service (e.g. ENT, Orthopaedics, General…), (2) medium term allocation of surgical services time into blocks across the available operating rooms (e.g. a Block schedule) and (3) short term allocation to patients to blocks of surgical time. The long term allocation of operating room time to surgical services is a strategic decision that takes into account known wait lists, further anticipated patient demand, hospital budgets and the priorities of hospital management. The allocation is normally expressed in the number of blocks of surgical time that will be allocated to each surgical specialty. Once the aggregate number of blocks has been decided, the second planning step is to create a medium term schedule for the blocks of surgical time, frequently referred to as a “block schedule”. A block schedule is typically a 3-5 week repeating pattern of blocks of surgical time for each of the available operating rooms. A good block schedule will smooth out the resources used across a set of ORs in a given day, and across the days of the week while respecting the overall allocation of time to surgical services, and constraints such as equipment and staff availability and post-operative care bed utilization. Generally, the more complex a surgical procedure, the greater its impact will be on hospital resources needed to provide pre- and post-surgical care. It is therefore important to consider the combination of resources needed for surgical services scheduled on a particular day as well as the combined impact that a sequence of days will have. Initially, a block schedule will specify only the timing of each surgical service within the schedule. In the past, the blocks might have been filled by specific surgeons (one per block) on a first come-first served basis, but common practice now is to either assign specific surgeons to each block, within their specialty, or to allow surgeons within the same specialty to schedule themselves into the assigned blocks timing. Once each surgeon knows his or her own surgical schedule, they may begin the process of assigning patients to the blocks. The number of patients that can be scheduled into a single block can vary depending on the procedure and its anticipated complexity. The final stage of creating a schedule is to assign a planned start and end time for each of the procedures within a block. This is analogous to a short term schedule in a manufacturing setting, and is considered a tactical decision.

Creating good block schedules is a challenging and iterative task, particularly if it is done manually, as it is done in many hospitals. Block schedules may need to be changed over the course of a year due to seasonal work schedules or if there is an arrival or departure of a surgeon that has a major impact on the demand for, or type of surgeries being conducted in the hospital. Because changes to a block schedule can create unanticipated peaks and valleys in resource utilization, they are therefore approached with the utmost caution and care. One of the biggest issues is to predict the impact that a change in a block schedule will have on the utilization of post-operative surgery beds. This is complicated by the fact that unscheduled emergency surgical procedures add to the use of resources.

In the past 20 years, there has been considerable interest in the process of creating good master surgical schedules by individuals skilled in optimization techniques (Guerriero & Guido, 2011). A variety of optimization models have been developed over the years, some of which focus on the ORs themselves (e.g., Blake & Donald, 2002) and others that recognize the importance of taking into account the impact a schedule has on downstream resources (Beliën & Demeulemeester, 2007; Beliën, Demeulemeester, & Cardoen, 2009). Several challenges with optimization techniques are that they result in very large scale problems for realistic settings, and they typically do not have a user interface that hospital staff feel comfortable using for what-if changes to the block schedule. They also do not typically take into account the impact of unscheduled emergency surgeries.

Most hospital staff responsible for developing master schedules are very experienced, and can create excellent schedules. What they have difficulty with is predicting resource utilization changes if, for example, a new block of surgical time is added and another removed, or if two blocks were to be exchanged or if a new operating room were to be opened. Few tools are available to assist staff with this process. A predictive rather than a prescriptive tool, as described in Vanberkel et al. (2011), proved to be a successful decision-support tool for a hospital in the Netherlands.

The skillset necessary to develop and successfully implement such a tool is well captured by a Management engineering education. Foremost is the ability to conduct a thorough system study so as to understand the problem at hand. Knowledge of classical probability theory and statistics, combined with notions of constrained optimization and queueing are necessary to be able to frame the problem and develop a conceptual model of the situation. In order to develop an effective decision support tool, computing and information technology skills are needed to furnish hospital staff with an interactive “what-if” interface to the background quantitative engine. Further, an appreciation for how hospital staff work is important if the staff are to support the use of a new system.

All industrial engineering programs provide students with a strong foundation in quantitative skills, but few provide more than introductory level computing or information technology courses or the opportunity to integrate these two areas with topics dealing with management of technological change. Management engineering builds on the analytical focus of industrial engineering, with a strong second technical thread – information technologies. And because people form a key component of any socio-technical system, a strong appreciation for the impact of technology is present.

Case Study: Computational Advertising

The great increases in computing power coupled with its decrease in cost and the ubiquitous networking of computers has led to significant new roles for engineers with skill sets common to the management engineer. More so than ever before, companies now maintain detailed records for every customer on what has been purchased, and in the case of online retailers, what has been viewed and many other details of customer interaction with the company. As a result, companies now have the ability to study their customers in much greater detail, but this increased detail requires engineers capable of manipulating large quantities of data and the knowledge of how best to analyze data to produce useful, actionable insights for a company's management. Many of these new jobs have titles such as “analytics engineer”, “data mining analyst”, “business systems analyst”, “data scientist”, “digital advertising inventory analyst”, etc. The online advertising industry typifies the work of these engineers, and we will use this industry as our example.

Advertising involves three key parties: the advertiser, the viewer of an advertisement, and the publisher that sells the display space for the advertising. On the internet, a publisher is usually a website. Each viewing of a page on the website by a user is known as an impression. The set of impressions on a website constitutes the website's inventory. The publisher can sell this inventory in several different ways. The simplest way to sell inventory is by charging a fixed price per impression. Typically, prices are quoted in a cost per thousand impressions or CPM, where the M is the Roman numeral for thousand. Advertisers will often want to buy a certain number of impressions spread out over a certain period of time. Satisfying a set of different buy orders from different clients can be complex as the demands for advertising will thus vary and so does the daily inventory on a website. If not scheduled carefully by the publisher, an advertisers' ads may have very uneven delivery and in some cases, users of the website may be saturated with ads from a single advertiser, which may decrease the user's opinion of the advertiser. Another common way to sell inventory is to charge for each click on an ad. In others words, each time a user clicks on an ad, the publisher charges the advertiser. This form of pricing is known as cost per click (CPC). CPC prices are typically much more than CPM prices, but the advertiser knows that they are only paying for users that have responded to the advertisement.

The publisher wants to maximize the money they can charge advertisers. The amount that can be charged for advertising is ultimately tied to value that advertising gives to the advertiser. Before online advertising, determining the return on investment for advertising was difficult for all but direct advertising, which is also known as direct marketing. Direct advertising sends a specific advertisement to a specific person and allows the advertiser to determine the ultimate success or failure of that advertisement. A classic example of direct advertising is direct mail, which is when an advertisement is mailed to a person. Online advertising is characterized by the ability to track and learn about the behavior of individuals at a detailed level. In effect, online advertising is direct advertising.

A key problem to be solved by a publisher is to make the best match between advertisers and the users of the website. The notion of best match is a complex problem of predicting which users will respond positively to a given advertisement. The better the match, the more the publisher can charge advertisers.

In the early period of the internet, publishers merely provided space and charged to display ads. As advertisers came to understand that they could track users by hiring third party ad-serving companies, advertisers started to learn that some websites were better matches for their ads than other sites. To predict which websites would be good for an advertiser before spending large sums of money, third party advertising firms such as Avenue A (later aQuantive and later acquired by Microsoft), began to offer advertisers what they termed behavior-based media planning (Song, 2012). Behavior-based media planning estimates the probability that a user of a website will visit the website of the advertiser's website. In its simplest form, this conditional probability can be calculated from large amounts of collected data (DeBusk et al., 2002). The idea being that websites with larger proportions of existing customers are likely to have larger proportions of users inclined to be responsive to the advertiser's message.

The matching problem is difficult on its own. Today, it often involves complex data mining and the analysis of web page content using information retrieval algorithms to best predict which ad should be shown on which page to which user (Essex, 2009). The problem is usually made more complex in that different advertisers are willing to pay different amounts for responses to their ads. For example, a luxury yacht dealer stands to profit more from a single sale than does a toothpaste maker. Combined with demands on how frequently users are allowed to see ads, the publisher has a very complex job of maximizing the value of their inventory.

Search engine companies such as Google and Microsoft provide search services to users for free in exchange for the chance to show advertisements to the users in addition to search results. While the search engines can build detailed profiles of their users, an important problem to solve is to determine the best match between a search query and the possible set of advertisements to show. The problem is characterized by having only a small amount of text from the user as well as only a small amount of text for the advertisement. This text matching problem has solutions based on typical information retrieval algorithms and involves the complex notion of even deciding when it is best not to show ads to a user (Broder et al., 2008).

The set of problems to be solved in computational advertising is unending. Not only do these problems involve the matching issue, but also economics and analysis of human behavior. For example, understanding how users respond to the type of page shown to them when they click on an ad can have a significant impact on the effectiveness of advertising (Becker, Broder, Gabrilovich, Josifovski, & Pang, 2009). These problems are the sort that management engineers are well suited to tackle with their strong mix of information systems, operations research, and human behavior knowledge.

Challenges and Issues for Management Engineering

We have characterized management engineering as a contemporary form of industrial engineering that addresses a changing economic landscape in which manufacturing has declined relative to other sectors, management systems have become increasingly technical due to the use of information technology, and analytical methods developed to solve manufacturing problems are now routinely applied in a wide variety of other management domains. Although these trends potentially threaten IE programs that focus narrowly on manufacturing, we believe they also offer significant opportunities for engineering schools to revitalize their IE curricula in ways that provide students with the IT skills and managerial knowledge needed to compete successfully in the job market. Industrial engineers have discussed potential institutional responses to these trends for some time, with proposals ranging from discipline name changes to curriculum redesign (Bailey & Barley, 2005; Elliott, 2008; Subramonium, 2008). The University of Waterloo's response has been to adopt the name management engineering and to design a curriculum that combines traditional IE analytics with substantial depth in IT, integrates social sciences relevant to understanding management processes, and focuses on a broad range of application domains beyond just manufacturing. Whether or not other engineering schools adopt similar strategies remains to be seen.

We believe that the term management engineering is more inclusive than industrial engineering, encompassing not only manufacturing and process industries, but also non-traditional industries in the service sector such as retail, finance, and advertising, and non-industrial domains like healthcare, military, and government planning. The term also signals a greater emphasis on the application of IT to management information systems than typical IE programs, while differentiating the discipline from software engineering or computer science. Finally, using the term "management engineering" to refer to the engineering of management systems is consistent with traditional naming conventions of other engineering disciplines, where for example "mechanical engineering" deals with the engineering of mechanical systems, "electrical engineering" refers to the engineering of electrical systems, and so on.

Nonetheless, as an emerging discipline, management engineering faces the challenge of overcoming assumptions held by some within the engineering profession that management is a social rather than technical domain of human activity and, therefore, should be considered as part of an engineer's complementary studies education rather than his or her core training. There are several ways of responding to such views. First, to reiterate an earlier point, we again distinguish between the practice of management and the engineering of management systems. Management engineering focuses on applying engineering knowledge and methods to design and implement the information systems, decision systems, and other operational systems that organizations use to produce products and deliver services, not the skills required to be a good manager. In short, management engineers engineer the systems that managers use to manage. Undoubtedly many management engineers will take on managerial roles as they progress through their careers, just like engineers from any other discipline. But engineering a management system is as different from being a manager as designing an airplane is from flying one.

Furthermore, we would argue that in many ways modern management systems are at least as technical as the factory systems traditionally analyzed and designed by industrial engineers. Management decision processes in healthcare, finance, logistics, retail, or transportation, often involve complex resource tradeoffs and information processing demands that require the use of rigorous analytical methods of optimization, probabilistic modeling, statistical analysis, or computer simulation. The analytical models at the heart of such processes are typically imbedded in computer-based information systems that integrate algorithms, databases, telecommunications, user-interfaces and related technologies. Designing both the analytical decision models and the software tools to implement these models are technical problems that management engineers are trained to solve.

At the same time, it is clear that management systems have important social and behavioural dimensions, and management engineers must be able to apply relevant social scientific knowledge to develop effective engineering designs. Management systems incorporate social phenomena such as behavioural and cognitive aspects of work; decision making; the collection, storage and processing of organizational information; economic transactions of many kinds; communication, coordination, and interaction between individuals, work groups, departments and organizations; and many more. Thus, management systems are essentially socio-technical systems, which combine social and technical processes in an integrated fashion. Management engineers need a good understanding of both the social and technical processes involved in management systems if they wish to model, improve, automate, or redesign these processes. Moreover, management engineering solutions change decision processes and reconfigure patterns of work behaviour, communication and interaction in organizations. And despite advances in computing power, the full social complexity of management systems cannot always be reflected in analytical or computational models. Management engineers need to understand the social dimensions of management systems to understand the processes they are modeling, to appreciate the limitations of their technical solutions, and to ensure that their solutions interface effectively with the organizational settings in which they are implemented.

The socio-technical nature of management systems means that social scientific knowledge plays a more fundamental role in management engineering than in most other engineering disciplines. However, this is not a reason to discount management systems as outside the domain of engineering, but an argument for expanding traditional notions of engineering as an applied science, to include the application of both natural and social sciences. For years, the CEAB (and other accreditation bodies such as ABET) have required engineering programs to include "complementary studies" in the social sciences and social impact of technology. Such studies expose engineering students to knowledge frameworks from other disciplines and help them understand how technical designs interact with the social contexts in which they are implemented. We argue, however, that social scientific knowledge is not just "complementary" to the study of management engineering, but part of the core scientific knowledge that management engineers apply to develop effective technical solutions.

Arguably, the same could be said of some other engineering disciplines. Knowledge of human social behaviour and motivation has played an important role in industrial engineering practice since at least the 1950s, when dissatisfaction with Scientific Management methods led to the "human relations movement" in factory work system design (Bailey & Barley, 2005; Roethlisberger & Dickson, 1956; Trist & Bamforth, 1951). More recently, software and computer engineers have developed a vast array of technical solutions to social problems in the telecommunications realm, ranging from diverse internet and World Wide Web applications, to smart phones and social networking technologies. The psychological sciences of human perception and cognition have become increasingly important in software and computer engineering practice related to human-computer interface design (Norman, 1988, 1993). In all these domains, good engineering design depends far more on an understanding of social scientific phenomena than on knowledge of natural sciences like physics or chemistry.

Accreditation rules that classify social sciences as “complementary studies” institutionalize a view that social knowledge is strictly separate from an engineer’s core technical training, a view which belies the socio-technical nature of many engineering problems. Such rules also limit flexibility in the design of engineering curricula, where schools must include natural science courses with little direct relevance to solving engineering problems within the discipline, but are given insufficient credit for core social science training that directly supports their students’ ability to develop effective engineering solutions. For example, many IE programs (and programs in other disciplines such as software engineering) require students to take several natural science courses to satisfy accreditation requirements, although the topics are rarely if ever revisited in later engineering science or design courses.

We believe it is time for the engineering profession to acknowledge that engineers apply knowledge from both the natural and social sciences in their design practice, and for accreditation rules to be updated to reflect this reality. Various potential revisions to CEAB accreditation rules can be imagined. For example, social and natural sciences could be grouped into a single “science” category, giving schools the flexibility to design a program of natural or social science courses most relevant to a given engineering discipline. Alternatively, depending on whether natural or social sciences are most relevant to a discipline, schools could be given the option of counting social science courses toward basic science requirements and counting natural science courses toward complementary studies requirements, rather than the reverse scheme prescribed by the current rules. More substantial revisions might include dispensing entirely with the input-based curriculum content rules as the CEAB evolves toward an outcomes-based accreditation regime.

Viewing management as an engineering domain creates obligations to approach the design of management systems from a professional engineering perspective. This entails ensuring that management engineering solutions are demonstrably robust and reliable relative to specified design requirements and that designs address both technical and social characteristics of the empirical setting in which they are implemented. Management engineering relies heavily on the analytical methods of operations research (OR), an academic discipline in which researchers have been criticized in the past for putting too much emphasis on abstract mathematical modeling, and too little on implementing analytical solutions or testing the empirical validity of models (Ackoff, 1979; Woolsey, 1972). Despite research priorities that emphasize novel contributions to mathematical OR theory, management engineers must be able to use OR methods to solve practical management problems in the real world. Educators must ensure that management engineering students are not only trained in mathematical theory, but also given the skills to test and validate OR models empirically, and to design and implement practical and reliable solutions to real management problems.

To address this issue, it may be instructive to consider how abstract mathematical models are used in disciplines like mechanical engineering, to represent problems in thermodynamics, solid mechanics, and other domains. As in OR, mechanical system models are often based on simplifying assumptions that abstract away many details of the empirical situation for the sake of conceptual clarity and mathematical tractability. When engineers use such models to analyze and design real mechanical systems, however, they typically incorporate empirically-derived correction factors to improve the degree of correspondence between model and reality. A great deal of research is conducted to collect the empirical evidence needed to establish valid correction factors, which enable engineers to use the abstract models with confidence in diverse design situations. When empirically-valid correction factors are not available, substantial safety factors are used to compensate for potential unknown model inaccuracies (for example, by over-engineering a load-bearing structure to support more than the maximum anticipated load.) Such correction or safety factors may not be appropriate for all management engineering applications, but we believe greater research emphasis should be placed on evaluating the degree of correspondence between important analytical models and the empirical situations being modeled. For example, the safe use of analytical models for therapeutic decision making in healthcare depends on a close fit between model assumptions and empirical data on health outcomes. More generally, because management decision models are used in organizations, management engineers must be knowledgeable of how various social and behavioural factors can cause organizational contexts to deviate from model assumptions. Simplifying assumptions are unavoidable when modeling complex problems, but to design systems that can be safely and reliably implemented in real management situations, management engineers need to be able to predict and correct for empirical errors due to model simplifications.

Finally, approaching management problems from an engineering perspective entails conducting one's work in ways that not only fulfil the technical requirements of the paying client or problem owner, but also protect public safety, ensure environmental sustainability, and satisfy the ethical and legal obligations of a regulated profession. The management domain has not always been subject to such professional constraints, and lacks many of the institutionalized regulatory frameworks, codes of practice, and design standards found in more established engineering disciplines. Educators must help students develop the skills to assess management engineering problems holistically, in terms of both their technical and ethical requirements, to avoid the ethical pitfalls they are likely to encounter as they progress in their professional careers.

Conclusion

Management engineering draws on the knowledge and methods of industrial engineering, software engineering, and computer science, but its focus on the engineering of management systems distinguishes it from these other disciplines. The emergence of management engineering reflects the increasingly technical nature of work and management systems in all sectors of the economy, whether public or private, service or manufacturing. Information technologies now play a central role in diverse organizational processes, from decision making to interpersonal communication, from financial transactions to the coordination of complex supply chains. Management decision processes draw on ever more sophisticated analytical methods and incorporate ever larger quantities of data. Work processes are increasingly rationalized and systematized. These societal and technological developments represent a tremendous opportunity for the engineering profession to play a prominent and influential role in the design and operation of management systems in the post-industrial era.

To take advantage of this opportunity, it is necessary to build the institutional frameworks needed to support and legitimize professional management engineering practice. The launch of an undergraduate management engineering program at the University of Waterloo is a significant step toward creating the needed institutions, but much more work is needed. As we have argued, professional accreditation rules that classify all social scientific knowledge as complementary rather than core to engineering practice, limit the flexibility of universities to design curricula most relevant and appropriate to management engineering. Management systems are fundamentally socio-technical in nature, so management engineers must integrate analytical methods and information technology with an understanding of the social and economic behaviour of organizations to design effective systems. More research on the empirical validation of analytical models is also needed, and the development of regulatory policies, ethical guidelines, and design standards relevant to the management domain would support the practical work of management engineering professionals. Until recently, management has usually been described as either an art or a science. With the increasingly technical nature of management systems, it can now also be legitimately claimed as a domain of engineering. It is up to the engineering profession to develop the institutions needed to support this claim.

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