Grand Challenges in Engineering

INFORMS – Institute for Operations research and the Management Sciences

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Overview

Operations researchers are trained in a range of quantitative methodologies that support the transformation of data into information for improved decision making. Operations research (OR) can be and has been applied in a broad range of engineering, economic, governmental, and social contexts. For example, OR is the core of the yield management systems used by every airline to allocate seats between full fare, reduced fare and frequent flyer (free) seats. Optimization algorithms developed by OR analysts are used by the major airlines in assigning crews to aircraft and in recovering from the inevitable disruptions that occur frequently in airline operations. OR analysis was behind the needle-exchange program that has been adopted to limit the spread of AIDS among intravenous drug users. OR has a long history of use in the design and operation of urban emergency services, identifying good locations for ambulance and fire station bases, suggesting relocation schemes when ambulances or fire companies are busy, and enhancing urban police patrol units. Industry uses OR results on a daily basis to schedule production runs, manage inventory and schedule employees. Last year's Edelman winner – the winner of the top prize for applied OR – demonstrated that OR can be used to improve productivity in the maintenance of C-5 aircraft. The result of this program was to reduce the average number of aircraft being maintained at any time by six, effectively returning six aircraft out of a fleet of 117 to active duty.

Several themes run through these examples. Operations research deals with understanding and developing the physics of complex systems involving people and technology, and ultimately with improving the operation of those systems. Operations research is concerned with the optimal allocation of resources and the pricing of such resources (e.g., seats on an aircraft, emergency vehicles, manufacturing equipment, and

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maintenance personnel). Operations research also facilitates the analysis of complex tradeoffs between objectives (e.g., the cost of deploying additional ambulances versus the reduction in average response time that can be expected as more vehicles are made available, or the cost of additional safety stock versus the reduction in material shortages that results from carrying additional inventory). Finally, OR deals with decision making under uncertainty (e.g., the number of seats to be sold on any given flight, the number of calls for emergency services in any day, future demand for a manufactured product, or the number of C-5 aircraft that will need routine or emergency maintenance next month).

Health care in developing countries

One of the key challenges facing the world today is that of providing adequate health care to the billions of people around the world who lack basic medical treatments, let alone access to more advanced diagnostic and treatment procedures available in much of the western world. Perhaps nowhere is this more evident than in Africa. More than one million children die each year from malaria, and the vast majority of them are in sub-Saharan Africa.[6] Over five out of eight of the estimated 38.6 million people living with HIV world-wide live in sub-Saharan Africa.[7] Reducing the mortality rates from these and other diseases in Africa and other developing regions of the world is a critical challenge for those living in more privileged countries.

The limited infrastructure (roads, power, water, etc.) often demand solutions that differ from those applicable in more developed areas. For example, in rural areas, patients may walk for several days to visit a clinic. Sending such patients home for two days while a remote lab processes the test makes little sense. Thus, there is often a need for new, fast, and accurate *local* diagnostic testing procedures that are economically viable on a small scale. The solutions to such problems will draw on the skills of numerous medical, political, economic, and social experts.

Potential role of operations research

Operations researchers will be able to play a key role in enhancing the decisions that will have to be made to mitigate the spread of such diseases in developing countries in particular and to enhance the level of health care in general. For example, with limited healthcare worker resources and pharmaceuticals, OR can elucidate the tradeoffs between allocating large amounts of resources to isolated areas with high infection rates versus allocating the same resources to less remote areas with lower infection rates. Caring for those in the isolated highly infected region may cure more people in the short run but, since these individuals are isolated, they may be less likely to spread the disease to other regions. On the other hand allocating resources to care for fewer people living in urban areas will result in fewer lives saved in the short-term but may reduce the rate at which new cases develop. Similarly, how should diagnostic testing equipment and kits be

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[6] http://www.amref.org/index.asp?PageID=50&PiaID=1

[7] 2006 Report on the global AIDS epidemic, A UNAIDS 10th anniversary special edition, http://www.unaids.org/en/HIV_data/2006GlobalReport/default.asp

allocated to different regions affected by a disease? More generally, how should resources be allocated between (1) treating those who are already sick, (2) improving the basic infrastructure (e.g., providing sewage systems and potable water) to reduce the spread of disease, and (3) educating families in nutrition and personal healthcare maintenance.

The infrastructure in much of the developing world is, almost by definition, under-developed. As such, the design of supply chains to deliver healthcare workers, equipment, and drugs to such regions is a challenging task that OR analysts are particularly well-trained to tackle. For example, how should inventory levels of perishable drugs be set and maintained in regions with low levels of electrification and refrigeration? How can workers and equipment best be deployed in areas with few roads? What are the costs associated with producing the equipment and kits locally as opposed to manufacturing them abroad and shipping them to the affected regions?

The solution to this problem will save millions of lives per year and will allow those in underdeveloped parts of the world to begin to realize the economic, educational and social benefits that citizens of developed countries take for granted.

Improved healthcare in the U.S.

Healthcare problems are not endemic only to developing countries. One out of seven people in the U.S. does not have healthcare insurance. The country suffers from chronic shortages of organs for transplantation. Access to diagnostic tests and treatment procedures differ dramatically across regions and socio-economic groups. Delays permeate hospital operations, reducing the effectiveness of existing resources. Improving healthcare access and treatment availability in the US in the coming decades will again be a major challenge facing the country. As in the case of healthcare in developing countries, individuals with a myriad of talents and backgrounds will be needed to craft an effective set of policies. Again, OR-trained specialists will play an important role.

Potential role of operations research

Many of the problems plaguing healthcare in the U.S. today relate to (i) the allocation of limited resources (e.g., Who gets the next kidney that is available for transplantation? How should surgical theaters be scheduled to maximize the number of patients treated per day? How can the availability of advanced diagnostic procedures be made more equitable across all segments of the population?), (ii) the inherently uncertain nature of the demand for services (e.g., How many influenza cases will there be next year? How do we identify the tipping point between increased influenza cases and a nationwide epidemic demanding emergency action on a national basis?) and (iii) tradeoff analysis (e.g., How do we determine whether it is better to spend $500,000 treating a single premature infant or providing pre-natal care to 1,000 indigent pregnant women? With limited federal dollars for healthcare, should funds be spent treating current diseases with known medications and procedures, researching new cures, or educating the public about

the benefits of a healthy lifestyle?) Again, OR-analysts can play a significant role in analyzing the underlying data, developing models to reflect alternative policies, and identifying key tradeoffs.

As in the case of developing countries, the resolution of this problem will result in improved healthcare and longer lives for millions of people at lower societal cost.

Using the internet to improve education in emerging countries

The Internet and satellite communications have opened virtually all parts of the world to information, news, education and more. For higher education in developing countries, this has provided a unique opportunity. Many of these countries have burgeoning young populations, often with 50% of the citizens less then 25 years of age. Capacity constraints at brick and mortar universities restrict the fraction of young people who can attend university to 2 to 4 percent of the population. This is in contrast to 40 to 60 percent in the developed western world. The Internet and communication satellites provide ways to increase dramatically educational capacity – via "distance learning" or "e-learning"– without building more brick and mortar facilities and without having to train thousands of new teachers[8].

As a result of these technological advances, distance learning initiatives have begun in scores of countries, a virtual A-to-Z from Algeria, to Brazil, to China, … to Zambia. As discussed in a brief video (http://linc.mit.edu/media.html), these initiatives are guided by a common dream:

With today's computer and telecommunications technologies, every young person can have a quality education regardless of his or her place of birth. By expanding educational opportunities worldwide, we will greatly increase the talent pool available to address new scientific, engineering, social, political, medical, and economic problems as they arise.

Many saw distance learning as a panacea, as a quick win where the only issue was acquisition and implementation of the technology. But soon it became apparent that the implementation of distance learning 'systems' was a much more complicated process than had been envisaged. More important than the technology was the environment in which the systems were being implemented, environment including economics, culture and tradition, content, pedagogy, work rules and more. Many countries tried to 'go it alone,' and learn only from their own mistakes. These same countries often proved to be naïve customers of marketeers brandishing the latest ICT's.

[8] Larson, R. C. and M. E. Murray, "Distance Learning as a Tool for Poverty Reduction and Economic Development: A Focus on China and Mexico," to appear, *Journal of Science Education and Technology*.

Potential role of operations research

Operations research, broadly defined as its founders intended, can play a significant role in helping developing countries achieve their goals with distance learning. OR can help in (1) defining goals and objectives, coupled with defined performance measures to chart success; (2) networked system design and selection of appropriate technologies subject to financial constraints and national infrastructure constraints; (3) deployment of personnel and capital assets; (4) design and creation of a maintenance and repair system, so necessary in developing countries; (5) design of a teacher training scaling algorithm, in which teachers would be trained, who would in turn train additional teachers, who would in turn utilize their new teaching skills in classrooms; (6) design of educational experiments, to test alternative pedagogical models; (7) design systems to help educators in different countries utilize Open Source educational content in e-learning, being aware of and sensitive to local cultural norms and languages.

Developing effective counter-terrorism strategies

Terrorism – the illegal use or threatened use of force or violence with an intent to coerce societies or governments by inducing fear in their populations, typically with political and/or ideological motives[9] – demands counter-terrorism. Given the reality that extant terror organizations have adopted a strategy of deliberately and indiscriminately murdering innocent civilians and disrupting society to achieve political ends, governments must respond proactively to protect the public, its infrastructure and its institutions. Other disasters-in-waiting such as earthquakes, hurricanes, the spread of infectious disease, or even the accidental failure of chemical or nuclear plants, are governed by chance or *probabilistic uncertainty*. By contrast, terror threats are governed by *strategic uncertainty* – terrorists decide when, where and how to strike to best achieve their strategic objectives. One consequence is that virtually all effective counter-terror tactics are transient – if government is able to develop a counter to a particular terror organization's mode of attack, communication, funding or recruitment, the terror organization will shift to a different set of tactics in pursuit of its goals. Against this backdrop, the government must decide what to do.

Potential role of operations research

Counter-terror decisions loom in the large and in the small. Resource allocation defending critical infrastructure is one large-scale issue situated squarely within the purview of OR[10]. Recently, the United States Congress changed the distribution of federal homeland security grants to state agencies from a formula that largely directed funds in proportion to state population. Arguing for the new bill, Sen. Diane Feinstein stated that "Al-Qaida and its allies do not attack based on a formula. This bill rejects the

[9] *Terrorism: Perspectives from the Behavioral and Social Sciences*, National Research Council, Washington, DC: National Academies Press, 2001, pp. 1-2.
[10] F Brown *et al.* Defending critical infrastructure. *Interfaces* 36(6):530-544;2006.

formula approach in favor of a framework that is flexible and risk-focused."[11] But what flexible, risk-focused approach simultaneously serves to allocate funds while recognizing that the nature of terror threats will change in response to whatever allocation is implemented? This is an OR problem. A different high-level problem relates to aggregating intelligence information of multiple forms from multiple sources to infer terrorists' current and future plans. Novel real-time methods for data-mining massive databases are needed to extract more and higher quality signals from intelligence information. As a third example, terror organizations have their own logistics and supply chains. OR models can be used to better understand how these chains operate, and hence to identify their weak points. Perhaps OR modeling could also translate an understanding of the inputs to and operation of terror production processes (e.g. procurement of explosives, bomb manufacture, recruitment of terror operatives, distribution methods) into an effective terror surveillance system. A narrower yet very important set of problems relates to the deployment and evaluation of specific terror-detection technologies, such as stand-off sensors for detecting suicide bombers from a distance,[12] biosensors for detecting a bioterror attack,[13] fingerprinting to detect known terrorist suspects from a watchlist,[14] certification, sensors and seals for detecting nuclear devices in shipping containers,[15] or airline security screening.[16] More broadly, for a given portfolio of counter-terror tactics in a given setting (e.g. counter-suicide bombing tactics in the Israeli-Palestinian conflict[17]), how does one know whether the array of tactics employed is actually helping or hurting? What are the marginal effects of different pieces of the counter-terror portfolio? OR is ideally suited for such operational evaluations of counter-terror tactics.

Using advanced sensor and telecommunication technologies to diagnose infrastructure faults

As the nation's physical infrastructure (buildings, highways, railways, bridges, dams, airports, sewage systems, power grids, etc.) age, and as the usage patterns change with demographic and economic changes, there will be a need to diagnose potential faults (e.g, cracks in bridges and dams, structural decay in buildings, etc) before major disasters reveal their presence. Technological advances in sensors and monitors, along with increased communication capacity will make continuous analysis of the state of the infrastructure possible. The collection of status, usage, and environmental data, together

[11] Congressional Record, Senate, July 12, 2005, p. S8093, http://tinyurl.com/yje8cz
[12] EH Kaplan and M Kress. Operational effectiveness of suicide-bomber-detector schemes: a best-case analysis. *PNAS* 102(29):10399-10404;2005.
[13] DL Craft, LM Wein, AH Wilkins. Analyzing bioterror response logistics: the case of anthrax. *Management Science* 51(5):679-694;2005.
[14] LM Wein, M Baveja. Using fingerprint image quality to improve the identification performance of the US Visitor and Immigrant Status Indicator Technology Program. *PNAS* 102(21):7772-7775;2005.
[15] LM Wein *et al*. Preventing the importation of illicit nuclear materials in shipping containers. *Risk Analysis* 26(5):1377-1393;2006.
[16] SE Martonosi, A Barnett. How effective is security screening of airline passengers? *Interfaces* 36(6):545-552;2006.
[17] EH Kaplan *et al*. What happened to suicide bombings in Israel? Insights from a terror stock model. *Studies in Conflict and Terrorism* 28(3):225-235;2005.

with advanced modeling based on both physical properties and observed incidents, will improve our predictive capability, allowing appropriate preventative measures to be taken.

Potential role of operations research

Operations Research can contribute to several aspects of this endeavor. OR models can be applied to determine, for a given budget, how many devices should be deployed, where they should be placed, and the frequency with which data should be collected. OR methods can also be used in the processing of the sensor data, including designing filtering strategies, archiving strategies, communication strategies for anomalous data, and in resolving conflicting information. Finally, in the event that the data from sensors indicate the need for action, OR methods can be applied to help determine the most effective allocation of resources for repairs and reconstruction.

Developing a self-sufficient sustainable energy program

Satisfying our nation's seemingly insatiable appetite for energy is already a grand challenge. In 2003, the US accounted for over 21% of the world's energy consumption while representing a mere 6 percent of the global population.[18] Developing energy self-sufficiency has been a topic in the US at least since the creation of the Department of Energy some 30 years ago. Indeed the DOE's first strategic theme entails "promoting America's energy security through reliable, clean, and affordable energy."[19] The private sector has been engaged in significant efforts to reduce our dependence on foreign oil, including the development of hybrid (gas/electric) vehicles already on the roads today as well as research on hydrogen-based vehicles.

Potential role of operations research

Operations research is poised to contribute significantly to the myriad of questions surrounding our national energy policy. In the short run, decisions must be made regarding the allocation of current resources between research in long-term energy sources and short-term deployment of known technologies. That such tradeoffs are difficult and that the correct choice is not immediately obvious is evidenced by varying decisions that different auto manufacturers have made regarding their corporate positioning along this research/deployment spectrum. As new technologies and energy sources emerge, new distribution systems and networks will be required. Operations research has a long and fruitful history in the analysis, design, and operation of effective and efficient networks, as well as the pricing of services in networked systems. This expertise will undoubtedly be called upon again in the design of new energy distribution networks (e.g., a network to distribute hydrogen for hydrogen-based vehicles). Also, in the development of alternative energy sources, critical tradeoffs will have to be made between enhanced self-sufficiency, cost and environmental impacts. Operations research

[18] http://earthtrends.wri.org/

[19] http://www.energy.gov/about/index.htm

analysts are trained in identifying and quantifying such tradeoffs to help elucidate the impacts of alternative decisions for policy makers.

Driverless highways and congestion mitigation

In highway transportation, the technology is rapidly converging for us to deploy driverless vehicles. GPS systems can identify the location of vehicles to within feet and local radar, optical, and sonic detection capabilities enable vehicles to locate other vehicles at even closer range. The Lexus LS 460 can already park itself (in ideal conditions)[20] as can the British Toyota Prius.[21] Cruise control in virtually every car on the market today regulates speed and engine operations thousands of times per second. By utilizing a computer-based vehicle control system we will be able to (a) increase utilization of the existing highway infrastructure through greater vehicle densities, (b) improve aggregate fuel economy, (c) reduced freight costs, (d) reduce travel time variability with the concomitant reduction in passenger delays and logistics costs associated with uncertainty and (e) enhance safety since the most unreliable component in any vehicle is the driver.

Potential role of operations research

While the future may seem clear in this case, the transition path to that future is less clear. OR can play a key role in identifying desirable implementation schemes. Questions that OR can help address (through such methodologies as stochastic modeling and simulation) include: (a) what overall level of system reliability is needed? (b) should the initial deployment of this technology be aimed at passenger vehicles or the commercial fleet? (c) how can a mixed fleet of vehicles enabled with this technology and those without it be managed effectively on existing highways? (d) by how much can the density of vehicles be safely increased? (e) how can equitable and efficient pricing schemes be developed for such systems?

More generally, congestion plagues much of the US infrastructure. One recent conservative estimate found that the cost of highway delays in the US was approximately $65 billion.[22] Delays at airports impact millions of passengers annually. Rolling brownouts are common in some states as a means of coping with electricity shortages during peak periods. For a myriad of reasons, we are unlikely to expand our existing infrastructure (highways, airports, waterways, etc.) in the coming years in the US. Thus, congestion will need to be addressed through other means including demand management, congestion pricing, and enhanced utilization of existing resources. Operations researchers have been at the forefront of developing these approaches over the last 50 years and will continue advancing the field in these areas. Such enhancements will return billions of hours of waiting time to the public for use in more productive activities.

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20 http://www.cjrdaily.org/the_audit/tempered_praise_for_the_amazin.php

21 http://auto.howstuffworks.com/self-parking-car.htm

22 http://mobility.tamu.edu/ums/congestion_data/tables/national/table_2.pdf

Medical imaging and enhanced diagnostic capabilities

Radiological and cardiac imaging procedures are converting from film to digital imaging at a rapid rate. The amount of medical image data stored in the US by the year 2015 range from several hundred to over 100,000 petabytes (1 petabyte = 2^{50} bytes or about 10^{15} bytes). By law, at least two copies of every medical image must be stored. This vast amount of data presents a number of opportunities. One such opportunity is to develop a set of computerized diagnostic tools (some of which already exist) to sit on top of the data and to examine the images for various abnormalities and pathologies. When problems are detected, the affected area can be highlighted on a separate "layer" of the image and a message can be sent to the physician suggesting that he/she reexamine the image. This could (a) enhance the early detection of disease, (b) improve physician training, (c) expand the geographic scope of expert image analysis to regions that are poorly covered by specialists today, (d) provide individuals with greater access to their own medical data.[23], (e) reduce diagnostic errors, and (f) increase productivity by allowing physicians to focus only on cases requiring their expert knowledge.

Potential role of operations research

Any such system will utilize carefully developed diagnostic tools that are based on advanced statistical techniques. Minimizing both the false positive and false negative rates will be critical. OR trained statisticians will contribute significantly to the development and deployment of such programs and systems. Also, with limited computing resources, such a system may need to make endogenous decisions about which new images to examine and which to ignore. Such decisions could be based on factors that include the severity of the patient's preliminary diagnosis and the past error history of the physician. OR models can help identify the images that are in the greatest need of computer-assisted diagnosis.

Summary

As indicated above, operations research can contribute significantly to the resolution of many of the grand challenges in engineering that the US and the world will face in the coming century. Most, if not all, of the challenges will require inter-disciplinary teams with experts from a variety of backgrounds each addressing different aspects of the issues. OR-trained experts are particularly adept at merging different perspectives and viewpoints and will therefore play a crucial role in the development of solutions to such challenges.

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[23] http://www.igreat.com/computerized_medical_diagnostic_imaging.html

Specifically, most of the grand challenges in engineering will require:

a) Carefully formulating the problems, defining the goals and objectives, identifying the key constraints, and sorting out the essential decisions that must be made. Indeed, developing answers to the following four questions is paramount in any OR analysis: (i) what do we know (the data) about the problem, (ii) what do we need to decide (the decision variables), (iii) what are we trying to achieve (the objective), and (iv) what inhibits our ability to do so (the constraints).
b) Making decisions about the allocation of limited financial, natural, or personnel resources
c) Analyzing large quantities of data and converting raw data into information for decision making.
d) Recognizing and coping with uncertainty about the future, whether that uncertainty reflects natural resource availability, human actions, future costs, or the effectiveness of alternative public and private policies, and
e) Dealing with tradeoffs and multiple objectives.

Operations Researchers are experts in exactly these areas. The examples above are but a sampling of the many challenges in engineering and public policy in which OR experts can and will contribute in the coming years.