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1 Introduction

It is often argued that operational research, once branded ‘the science of better’, should play a key role in the analysis, design, and improvement of healthcare services.[1–3] But, despite some penetration into health systems, staff in many areas of health service planning, operation, and improvement may remain largely unaware of operational research and its potential applications.

In this Element, we first discuss the origins of operational research. We then give an overview of its application to improve healthcare services. Operational research comprises a wide range of methods and techniques and we do not attempt to cover them all here. Rather, we introduce some of the key concepts and common approaches before giving brief accounts of healthcare applications that demonstrate the range, potential, and, just as importantly, some of the limitations of the discipline. We also discuss some of the challenges of incorporating operational research into improvement initiatives and of working with operational researchers.

We focus predominantly on examples from the National Health Service (NHS) in the UK. And, where possible, we discuss work published in journals aimed at healthcare professionals or managers rather than examples published in technical journals targeted at other operational researchers.

2 What Is Operational Research?

In this section, we introduce definitions both of operational research and of the models that operational researchers construct when trying to solve problems. We also give an overview of the wartime origins of operational research. We then introduce a selection of the many different approaches that operational researchers may adopt when working to improve health services, before discussing some of the preparatory steps and behaviours common to these.

2.1 Operational Research as a Collection of Modelling Techniques

Operational research (referred to as operations research in the USA) can be viewed as a collection of conceptual, mathematical, statistical, and computational modelling techniques used for the structuring, analysis, and solving of problems related to the design and operation of complex human systems. These techniques range from approaches that systematically map the perspectives of individuals, professions, or organisations impacted by the problem being addressed, through to approaches for building and experimenting with a highly detailed mathematical or computational analogue of a healthcare service. A common element in these techniques is that the operational researcher, at some point in the course of their work, develops a ‘model’ of the system or problem.

The term model means different things to different people. Pidd gives the following definition for what operational researchers mean by a model in his excellent book *Tools for Thinking: Modelling in Management Science*:

> *A model is an external and explicit representation of part of reality as seen by the people who wish to use that model to understand, to change, to manage, and to control that part of reality.*[4]

We note that Pidd explicitly avoids the term ‘improvement’ in his definition, to acknowledge that an improvement from one perspective may constitute a worsening from another equally valid perspective. That said, many of the techniques introduced in this Element assume that the purpose of change is clear and agreed. As we will discuss, this can limit the acceptability of operational research techniques in some healthcare contexts.

Although a definition of operational research as a collection of certain modelling techniques works at one level, it is incomplete. The list of techniques deployed by operational researchers evolves over time and many people may use one or more of the techniques without identifying what they do as operational research. Indeed, the set of techniques used in operational research includes the theory of constraints and overlaps with those used in systems engineering, operations management, and industrial techniques such as Lean (see the Elements on systems mapping,[5] operations management approaches,[6] and Lean and associated techniques for process improvement[7]). To understand what binds the collection of techniques into a discipline, it is useful to cover the origins of operational research.

2.2 The Wartime Origins of Operational Research

Some of the techniques that comprise operational research were in use before the 1930s, for instance in the analysis of telecommunication networks and in the industrial time-and-motion studies of Taylor and others.[8] However, the term operational research was coined, and the discipline forged, immediately before and during the war effort of the Allied powers in the 1939–45 conflict of World War II.[9] Growing out of research related to the use of radar, academic scientists from different disciplines (including physicists, chemists, and geneticists) worked with the armed forces to frame and tackle the problems they faced, many of them related to the efficient deployment of resources. For example, one problem was to determine the optimal size of merchant convoys in the Atlantic Ocean that would minimise the losses of craft to submarine attacks given a fixed

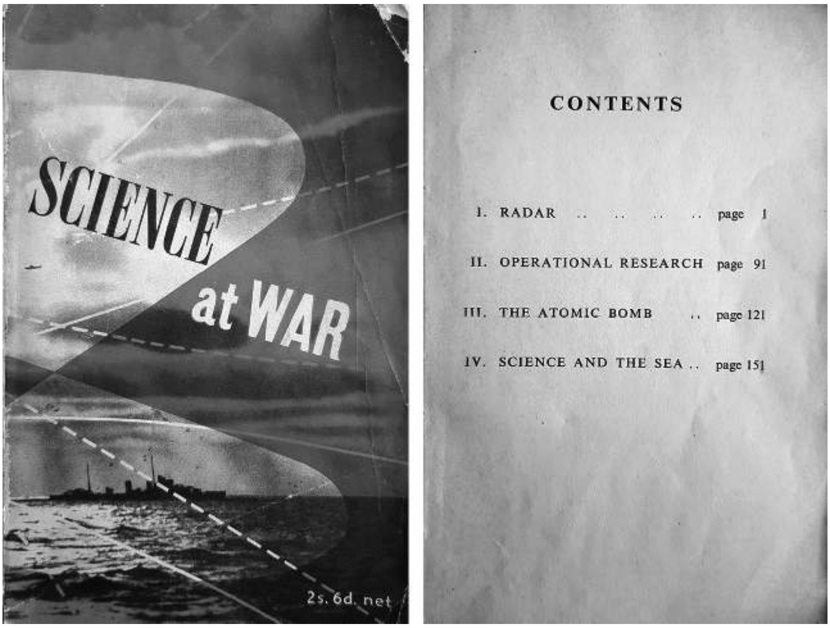

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Figure 1 Front cover and table of contents of the 1947 HMSO publication *Science at War*,[9] showing the billing given to operational research

Cover design by Eileen Evans. Document held by The National Archives. Contains public sector information licensed under the Open Government Licence v3.0.

availability of escort vessels. Another was how to increase the flying time of aircraft providing cover to convoys during attacks.

Figure 1 gives some indication of the importance attached to operational research at the end of the war, with the 1947 HMSO publication *Science at War*[9] giving as many pages to discussing operational research as it does to the atomic bomb.

2.3 Operational Research as More than a Collection of Techniques

Key to the success of operational research during the war was the acknowledgment by scientists that while they had expertise in data analysis and in using scientific methods to understand complex physical or biological systems, they did not understand warfare. To be useful, they needed to spend time listening to, learning from, and working alongside staff at all levels of the armed forces.

This was epitomised by Patrick Blackett, a professor of physics (and 1948 Nobel Prize winner) who served during the war as scientific adviser to the commander in chief of anti-aircraft command and as director of operational research for the admiralty. His wartime principles for effective operational research, reproduced by Royston,[10] included that it should be both:

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- **collaborative**: ‘An operational research section should be an integral part of a command and should work in the closest collaboration with the various departments at a command’
- **grounded**: ‘All members of an operational research section should spend part of their time at operational stations in close touch with the personnel actually on the job’.

This recognition – that collaboration with workers at different levels of organisations and respecting their knowledge and experience are crucial – characterised the successful use of operational research across many industries in the postwar period, with large operational research groups formed within the coal and steel industries and in the railways.

In this sense, operational research is better defined as an ethos of problem framing and solving: applying scientific method and modelling techniques in collaboration with problem owners and subject experts to help understand and change the operation of complex organisations to some defined purpose. The textbook description of an operational researcher is someone who helps decision-makers frame their problem in a way amenable to systematic, rational analysis and then deploys the right tool for the job to solve the problem at hand. In reality, individual operational researchers rarely have proficiency across the whole spectrum of operational research approaches.

2.4 A Selection of Operational Research Approaches

In this section, we give a brief comparative account of several key approaches from the operational research toolkit, highlighting some of their applications in healthcare. For simplicity, we have grouped these into broad categories based on whether the primary intent of using the approach is to solve a well-defined decision problem with an agreed objective, to account for multiple perspectives on a problem, or to describe the behaviour of a system. We then discuss the use of combined approaches and the development of hybrid models.

2.4.1 Approaches for Solving Well-Defined Problems

First, we introduce the concept of optimisation. A frequently used example is the manufacture of cylindrical tin cans. Both the surface area and the volume of a cylinder can be calculated as functions of its height and the radius of the circular ends. Optimisation techniques can be used to identify for the manufacturer the single combination of height and radius that minimises the surface area of tin used to contain a given volume of soup (see Figure 2A).

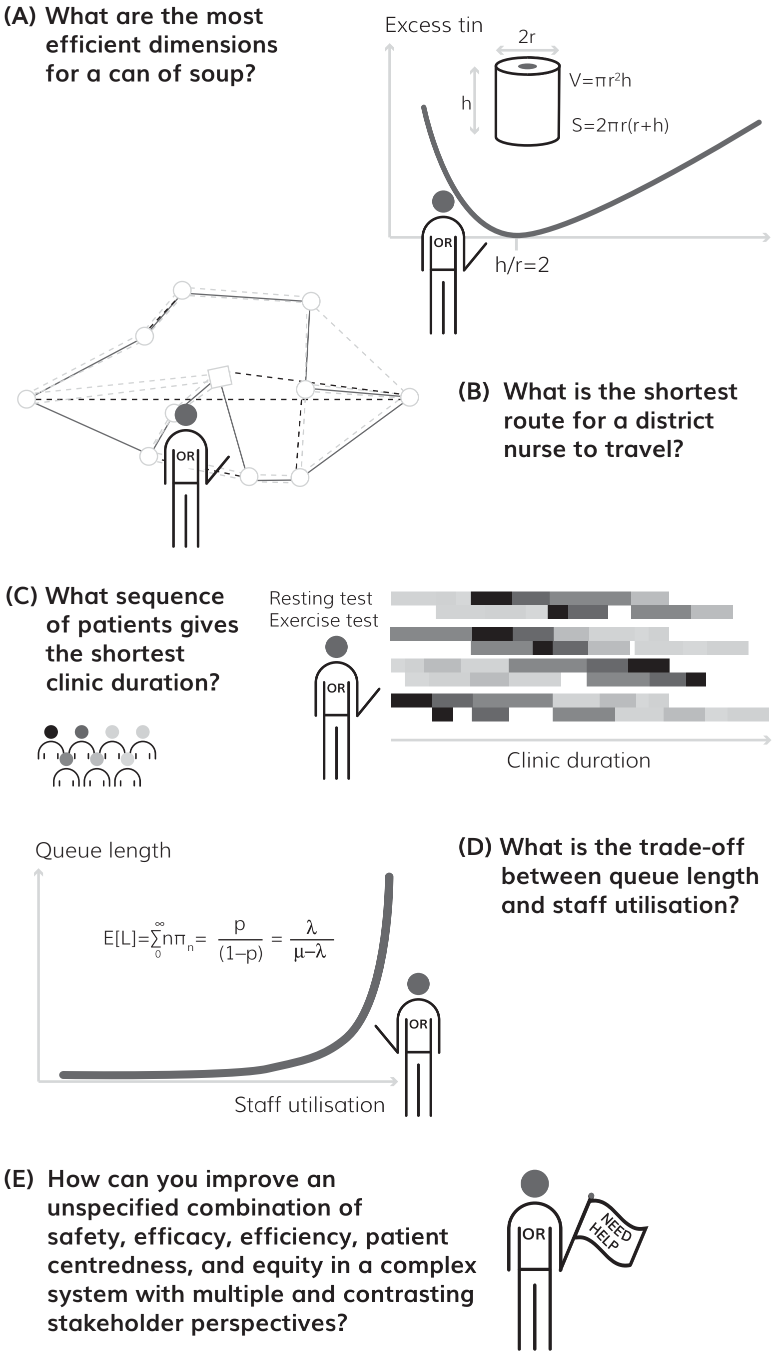

Figure 2 Examples of problems amenable to operational research
OR = operational researcher

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A key step in many of the approaches outlined in this Element is defining, for the sake of analysis, the purpose of the modelled system. This chimes with the focus of other improvement methods on defining what ‘good’ looks like and addressing the question: ‘how will we know if we’ve made an improvement?’ In operational research, this often involves writing down an ‘objective function’, which is a mathematical expression to quantify a key aspect of system performance. For a tin can, this is the equation expressing the surface area of the can in terms of its height and radius. In healthcare applications, this might be the distance travelled by a district nurse in terms of the order in which patients are visited (Figure 2B), or the duration of a clinic depending on the sequence of patients (Figure 2C).

Mathematical Programming

Mathematical programming is a group of optimisation techniques designed to identify how a system can be optimised by changing those features of a service considered to be under the control of decision-makers (called the design parameters or decision variables). A set of equations is constructed to relate the decision variables to the objective function and to other aspects of the system considered important (for instance, resource constraints or performance standards that must be met). A step-by-step process of calculation (called an algorithm) is deployed to identify a set of values for the decision variables that achieve the highest (or lowest) value for the objective while meeting the constraints. The algorithms used in mathematical programming are proven to work only for objective functions where the relationships between decision variables and objectives and constraints are relatively simple. Even then, they can be impractical for problems with a very large number of decision variables and constraints. Some problems in healthcare, while theoretically amenable to mathematical programming, would take many hours or even days or weeks of computer time to solve using these methods, which is too long if the problem needs to be solved on a daily basis. In such circumstances, researchers often turn to heuristic approaches, as described in the following paragraphs. For an overview of mathematical programming and other optimisation approaches applied in healthcare, see Crown et al.[11]

Heuristics and Heuristic Search

Heuristic approaches to problem-solving involve devising a set of rules to be applied, often iteratively, for obtaining acceptable solutions to problems, typically without any guarantee of finding an optimal solution. For the district nurse in Figure 2B, a simple heuristic would be to iteratively apply a rule of visiting the nearest patient they have not yet visited. Heuristic problem-solving has particular value in areas of scheduling and transportation and in staff rostering (see the discussion on nurse rostering in acute settings in Section 4.5).

Heuristic search is an alternative approach to improving the performance of a modelled system, in which a set of rules guides an iterative search of possible combinations of decision variables for a particular problem. Again the intent is to find a sufficiently good solution within acceptable computational time, without a guarantee that the solution is optimal.

2.4.2 Approaches to Account for Multiple Perspectives

Mathematical programming and heuristic search approaches assume, for the purposes of model building, that the objective of change is well-specified and agreed. This is often not the case, particularly in healthcare where patients, staff, and the management of different organisations within the system may take different views on the root of the problem being addressed, the desirability of different interventions, and the relative importance of different performance metrics.

Soft Systems Methodology

Problem-structuring methods are a group of operational research approaches that explicitly reject the notion of optimality in favour of identifying feasible courses of action that are acceptable to a group of stakeholders, while respecting that stakeholders will bring different values and value systems to the appraisal of alternatives.[12] For instance, patients, primary care clinicians, secondary care clinicians, and commissioners might all have different and valid perspectives on what constitutes a good quality healthcare service.

Soft systems methodology is one such approach that acknowledges and engages multiple perspectives.[13,14] It was developed to address complex multi-perspective issues through systematic learning about the problem and the relevant decision processes and mechanisms of change. Soft systems methodology involves developing a detailed account of the problematic situation motivating the desire for change, often in the form of a ‘rich picture’ depicting the people and organisations involved in a service, the issues as perceived from different perspectives, and the characteristics of potential improvements from a systems thinking perspective.

The researcher builds detailed conceptual models that articulate, in a systematic way, the different ‘world views’ (motivations, priorities, and constraints) of the different stakeholders. Through this process the researcher uses probing questions that identify feasible options for change and the likely impact of such changes. Augustsson et al. provide an overview of the application of soft systems methodology in healthcare.[15] Notable examples of UK works include efforts to improve postoperative services for infants with congenital heart disease that identified which patient groups to target with interventions such as home monitoring and multidisciplinary care teams,[16] and work at an acute hospital that identified simplifications in paperwork and a process for more frequent patient reviews which, when combined, reduced delays to discharge by 40%.[17]

Multi-Criteria Decision Analysis

Multi-criteria decision analysis is another set of operational research techniques designed to support decision-making in contexts where stakeholders may have markedly different perspectives on the relative value of different aspects of a system's performance. A quantitative model is built that links the characteristics of different options for change to the different metrics of performance that are of interest to the stakeholders.

One powerful strategy of multi-criteria decision analysis is to identify and discard options for change that are worse than others from at least one perspective and no better than others from any other perspectives. Other techniques within this approach are then used to build a shared understanding of the trade-offs between different perspectives, and to analyse individual and group preferences among options. Note that if there is no difference in opinion as to the relative importance of different criteria, multi-criteria decision analysis can simplify to a form of mathematical programming.

The application of multi-criteria decision analysis in healthcare is predominantly focused on questions of health policy or health technology assessment.[18,19] That said, example applications in the area of improvement include an exercise to support budgetary decisions in multi-agency initiatives to reduce teenage pregnancies in London, which suggested shifting investment from clinical services to other areas such as media campaigns and sex and relationship education,[20] and choosing between sites for a new health centre in the north of England based on assessments against seven weighted criteria, including the total cost, accessibility, and design of different options.[21] An example application in improving postnatal care is described in Section 4.4.

2.4.3 Approaches to Describe System Behaviour

The modelling approaches discussed in this section are intended primarily to offer a way of describing the behaviour of a system under a range of circumstances. These approaches are often used to determine and illustrate trade-offs between different aspects of system performance and to explore the likely impact of changes to the configuration or operation of a system.

Computer Simulation Modelling

The term simulation describes a wide range of research and training activities (further discussion can be found in the Element on simulation as an improvement technique[22]). Within operational research, simulation modelling involves constructing a model of the key components of a system. For instance, if simulating use of an emergency department, the components might be, for example, reception, triage, X-ray, minors and majors, along with the queues for each. The operation or behaviour of each component is specified by mathematical expressions or a set of rules, as are the relationships between components and the flows between components of patients, information, or other entities.

Simulation has wide application in healthcare.[23] In operational research, typically (but not exclusively), simulation is used when the nature of activities modelled at each component and the relationships between components are complex, such that the behaviour of the whole system over time and under different circumstances cannot be readily inferred from inspecting a set of equations. For instance, the time-dependent arrival patterns of patients to an emergency department, the subsequent prioritisation among evolving sets of patients based on clinical acuity, and the interplay between diagnostic processes, clinical decision-making, and how the flow of patients depends on the capacity available in other parts of the hospital cannot be modelled accurately without simulation. Learning about the system is instead generated by running the simulation on a computer and analysing the behaviour it exhibits, qualitatively or quantitatively, through the statistical analysis of model output. Features of the model corresponding to design parameters can then be changed (e.g. changing demand for services, or numbers of staff or beds) and the impact of these changes on model output can be analysed through experimentation.

Macro-simulation approaches, such as system dynamics, consider the high-level behaviour of a system and can be used to identify negative and positive feedback effects in complex healthcare systems. One example application is system-wide capacity planning for osteoarthritis in Alberta, Canada.[24] A review by Cassidy et al., written for a health services research audience, found that such approaches are often used to explore unintended consequences of proposed policies in urgent and emergency care and other highly connected systems[25] – for example, improvements designed for one target patient group having detrimental consequences for other users of the same service.

Micro-simulation approaches, such as discrete event simulation, operate at a patient level. Variables – such as the time between successive patients arriving, the duration and outcome of different clinical activities, and so on – are chosen at random from distributions on a patient-to-patient basis. The simulation model is then run hundreds or thousands of times for each experiment, sufficient for statistical analysis of the output from the model to generate meaningful insights. An example of computer simulation modelling to improve acute stroke care is discussed in Section 4.1.

Queueing Theory and Related Analytical Models of Patient Flow

Queueing theory is the mathematical analysis of how customers (or patients) flow through connected systems of processes (care activities) and the delays incurred as queues form and dissipate. The application of queueing theory involves using standard queueing equations, or deriving new ones to explore the performance of a system. Performance metrics include queue sizes, the waiting times experienced by different priority groups, the utilisation of resources, and the number of customers that baulk at the size of the queue or that join a queue but leave before being served. Applications in healthcare include capacity planning for specialist clinics,[26] understanding flows through mental health services,[27,28] and developing models to inform the staffing of accident and emergency services.[29]

Standard queueing equations are based on assumptions about how the time between the arrival of successive patients and the duration of care activities vary from patient to patient. For many real-world systems, these assumptions do not hold. This places some limitation on the validity of queueing theory results related to these systems, and perhaps a greater limitation on the acceptability of queueing theory to those working in the service. However, queueing theory remains a powerful tool to explore and communicate intrinsic trade-offs between different aspects of service performance due to day-to-day and patient-to-patient variability and uncertainty in terms of arrivals, treatment times, and lengths of stay (see Figure 2D).

2.4.4 Hybrid Models

In many operational research projects, the operational researcher uses more than one method, either through a comparative process of triangulation or with the output of one method feeding into another.[30] Hybrid models take this one step further, with one method embedded in another, or two computer implementations of operational research methods exchanging information iteratively in a combined run.[31] For example, a composite discrete event and system dynamic simulation model was used to look at the interaction between the operation of chlamydia screening clinics and the population-level dynamics of infection.[32]