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Invited Review

Operational Research in education

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ABSTRACT

Operational Research (OR) techniques have been applied, from the early stages of the discipline, to a wide variety of issues in education. At the government level, these include questions of what resources should be allocated to education as a whole and how these should be divided amongst the individual sectors of education and the institutions within the sectors. Another pertinent issue concerns the efficient operation of institutions, how to measure it, and whether resource allocation can be used to incentivise efficiency savings. Local governments, as well as being concerned with issues of resource allocation, may also need to make decisions regarding, for example, the creation and location of new institutions or closure of existing ones, as well as the day-to-day logistics of getting pupils to schools. Issues of concern for managers within schools and colleges include allocating the budgets, scheduling lessons and the assignment of students to courses. This survey provides an overview of the diverse problems faced by government, managers and consumers of education, and the OR techniques which have typically been applied in an effort to improve operations and provide solutions.

1. Introduction

Education covers a range of sectors from kindergarten, primary and secondary schooling, to post-compulsory and higher education. The expected years an individual might spend in education in total can vary considerably across countries; within the OECD, for example, a person in Indonesia can typically expect fewer than 14 years whilst one in Finland nearly 20 years (OECD, 2013). An interesting dimension of education is that consumption at some levels is compulsory while at other levels it is voluntary; and because an individual's consumption of education has both external and private benefits, it is often (but not exclusively) provided through public funding.[1] This market failure and consequent public funding engender government intervention in the form of planning and resource allocation across the education sectors. These are complex areas, but they are ones where Operational Research (OR) tools can be effectively used to aid policy-makers (Platt, 1962).

Top-level planning and resource allocation are not the only areas where OR can be useful. Education managers are faced with a plethora of problems in the day-to-day running of their institutions. These relate, for example, to the optimal allocation of their budget, or simply to where each class should take place and who should teach it. OR also has the tools to address these problems as is testified by the vast OR literature devoted to management, timetabling and scheduling in education.

OR originated as a tool to aid the military. In 1936, applied research into radar technology and its application in a military setting was undertaken jointly by British air force officers and civilian scientists. This led to the formation of Operational Research groups in the UK and operations research groups in the USA which brought together scientists from a variety of disciplines to solve problems encountered in a military context – encompassing the army, navy and air force (Gass, 1994; Gass & Assad, 2005; Kirby, 2003; Weir & Thomas, 2009). Once World War II was over, OR groups continued to be supported, with the focus switching to logistics, modelling and planning. It became apparent that OR had a place in solving operational problems in organisations unrelated to the military (Gass, 1994), and so applications of OR techniques to business quickly followed the end the War. Indeed, the competitive advantage and consequent increase in profits enjoyed by firms which successfully applied new OR approaches in their operations were strong inducements to making OR an acceptable approach to solving problems in the business setting (Horvath, 1955).

Operational researchers were, however, much slower to apply their skills in areas of public provision of services such as education, health, police and fire services. The lack of profit motive meant that there was a danger that these areas might remain ignored. Early publications called on operational researchers to become involved in studying the complex problems seen in provision of education (Dean,

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[1] Public spending on education averages 13 percent of total public expenditure across all OECD countries, and is more than 20 percent in some countries (OECD, 2013).

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1968; Griffin, 1968; Horvath, 1955; Platt, 1962; Rath, 1968; Shepherd, 1965) and demonstrated the relevance of OR tools in addressing these issues (Blaug, 1967b; Van Dusseldorp, Richardson, & Foley, 1971). Education has been firmly on the OR agenda since that time.

This paper examines the following questions in the context of education. What types of problems has OR typically tried to address? Which OR tools are commonly applied? No attempt is made to provide a review of all OR applications to education but rather to give a flavour of the areas where OR tools have been used. While references are largely confined to mainstream OR journals, there is inevitable reference to similar applications appearing in mainstream economics or education journals where there is often a parallel literature. Each section of this paper addresses a specific topic within the field of education and discusses the techniques which have been used to address it. The main areas of coverage are planning models (Section 2); efficiency and performance (Section 3); and routing and scheduling (Section 4). Section 5 concludes and considers areas in education still to be explored by operational researchers.

2. Planning and resource allocation

The call for OR to be applied within education coincided with a burgeoning demand for education and training: the post-War period saw increasing birth rates in many Western economies as well as rapid economic and social changes which required an increasing supply of educated manpower (Blaug, 1967a). There was a growing recognition that economic progress and growth required investment in both physical and human capital (Armitage, Smith, & Alper, 1969; Weisbrod, 1962). The expansion of education provision required accompanying resources, and so it was important to be able to predict student numbers at different education levels and hence resource requirements. Early forays by operational researchers into the field of education were therefore attempts at assisting education and manpower planners (see Schroeder, 1973 for an early review).[2]

2.1. Planning

The education sector can be seen as a series of components (i.e. different levels of education such as primary, secondary, vocational and tertiary) which are interconnected in such a way that each individual can follow a pathway which meets his own educational and training aspirations (Tavares, 1995). Education is therefore a system; adopting this view allows operational researchers to model the system using a variety of approaches and provide useful forecasts for managers, planners and policy makers.

Planners are interested in projections of students and of needs (in terms of teachers and equipment) at all levels of education. Goal programming can be used to determine optimal numbers of students (at macro- and micro-levels) as demonstrated by an early study of vocational education in Missouri (Atteberry, 1979) and another on determining the optimal admissions policy for an individual institution (Lee & Moore, 1974).

A more commonly-used approach to educational planning, however, presents the education system as a series or flow of mathematical relationships (Van Dusseldorp et al., 1971). Studies differ in the mathematical representation – a simple Leontief input-output depiction of interdependence between students at various education levels (Oliver & Hopkins, 1972; Stone, 1965, 1966); a sequence of discrete events in time (students in different modules on a programme, for example) to which simulation can be applied (Saltzman & Roeder, 2012); a Markov chain framework based on students in each state (education level, for example) and their probability of moving to another state – but all are capable of providing forecasts of student numbers.[3]

It is particularly attractive to view the education system in the framework of a Markov process which is defined as an ordered series of states linked by a transition matrix composed of probabilities of moving from one state to another. So in a college setting we might consider students to be in any one of the following states: studying full time; studying part time; on a temporary leave of absence; successfully graduated; or withdrawn (Kwak, Brown, & Schiederjans, 1986). From past data it is then possible to estimate the values of the transition matrix and use these to make predictions of student numbers at any stage.

Many examples of the application of mathematical models to education planning exist at both national and institution level (Armitage & Smith, 1967; Brandeau, Hopkins, & Melmon, 1987; Clough & McReynolds, 1966; Correa, 1967; Forecasting Institute of the Swedish Central Bureau of Statistics, 1967; Gani, 1963; Gray, 1980; Harden & Tcheng, 1971; Hopkins & Massy, 1977; Kwak et al., 1986; Massy, 1976; Nicholls, 1983, 1985; Smith, 1978; Thonstad, 1967). Because they are based on student flows from state to state, Markov chain models have proved particularly useful at the faculty and programme levels in providing not just predictions of students but also additional insights into, for example, non-completion both in postgraduate programmes (Bessent & Bessent, 1980; Nicholls, 2007) and undergraduate programmes (Shah & Burke, 1999), required deployment of supervisors in a doctoral programme (Nicholls, 2009), and evaluation of the efficacy of early-retirement programmes for university faculty (Hopkins, 1974). There are fewer examples of the application of simulation to students flows; one such study, however, has proved useful in evaluating the potential effects on students, in terms of their time to complete the programme and graduation rates, of changes in curriculum provision brought about by recent budget cuts (Saltzman & Roeder, 2012).

These planning models rely heavily on underlying assumptions such as those relating to the transition rates, and these in turn are often based on historical data. For planning at a school level, the transition proportions will need to be adjusted if, for example, there is a change in birth rates, migration, expansion of educational provision in the local area, or increase in residential building in the catchment area (Smith, 1978). More satisfactory models can be derived by altering the transition proportions to reflect additional uncertainty (Armitage et al., 1969; Massy, Grinold, Hopkins, & Gerson, 1981). Even so, the models are highly descriptive and do not provide any indication of how or why the numbers observed in the system emerge. Only insofar as the system continues to behave in the future as in the past will projections be accurate.

2.2. Resource allocation

These mathematical flow models generally used in planning fail to answer the question of what is the *optimal* policy for planners (Alper, Armitage, & Smith, 1967; Correa, 1967) and this leads on to the issue of optimal allocation of resources. Governments need to know not just how many students to expect at each education level, but also how much money is required to fund the predicted numbers. An individual education authority or school must also allocate its resources to provide education in line with predicted demand. But for the education system as a whole, or for an organization within the system, potential conflicts between competing objectives must be reconciled. This leads us into multi-objective decision-making in which goal programming is a popular methodological approach, and indeed has

[2] The importance of OR in developing models for assisting in educational planning in the UK is revealed in Ladley (1987) who describes the models developed by the OR Unit of the Department of Education and Science.

[3] Of course, if the model is set up in terms of staff or financial resources, then forecasts of those variables can be derived.