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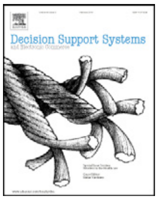

A decision support system for patient scheduling in travel vaccine administration

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ABSTRACT

The administration of travel vaccines presents a number of operations management challenges. The interplay between shared consumption of multi-dose vaccine packages, rapid spoilage upon opening, the high cost of wastage, and the unique vaccination needs of the patients makes for a very interesting and complex scheduling problem that could benefit from computerized decision support. We compare the performance of a novel binary integer programming model and a genetic algorithm solution technique with conventional scheduling approaches. Computational results show that significant cost savings can be achieved with the DSS while simultaneously considering scheduling preferences of patients and mitigating scheduling inconvenience.

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1. Introduction

Health care costs are one of the most pressing economic problems of our time. As such, computerized decision support that leverages sound operations research and management science principles has a unique opportunity to assist medical professionals in ensuring the delivery of services in the most efficient means possible. This paper considers one such opportunity.

With the rising cost of prescription medicines, reducing waste in the delivery and administration of pharmaceutical products has become of increasing concern [31]. Management of pharmaceutical stock is often regarded simply as an issue of perishable inventory management, a field well-studied by management scientists over many decades—for a review, see Ref. [40]. However, while conventional perishable inventory management may apply for many prescription drugs, there is a field of medical practice where the inventory management problem is atypical: the field of travel vaccine administration.

The United States Centers for Disease Control (CDC) recommends a variety of routine, recommended, and required vaccines for travelers to foreign destinations [7]. For example, when traveling to South Africa, the CDC recommends travelers be brought up-to-date on all routine vaccinations (including measles, mumps and rubella; diphtheria, pertussis, and tetanus; polio, and others), and also receive additional immunizations for hepatitis A, hepatitis B, typhoid, and rabies.

Travel vaccine administration presents peculiar challenges to management scientists for numerous reasons. Firstly, many vaccines are packaged in multi-dose vials such that the contents are administered to several patients (shared consumption). Secondly, each patient typically requires a particular combination of vaccines, depending on their planned destination of travel and prior immunization history; therefore, consumer assortment demands are particularly stringent. Thirdly, and most critically, once opened or reconstituted, many vaccines must be used within a very short time-span, or discarded, due to rapid spoilage when exposed to air and room temperatures [2,60]. Finally, vaccines are costly to produce, making wasted doses quite expensive. For instance, YF-Vax® (yellow fever vaccine), is available in multi-dose vials with a shelf-life-once-opened of 60 min [44]. YF-Vax® wholesales for over $340 per multi-dose vial [51], with each wasted dose costing the medical practice almost $70. A single dose formulation is also available, as an alternative to the multi-dose vial, but the per-dose cost is 25% higher for the single dose formulation [51], so clinics should prefer the multi-dose formulation if no doses will be wasted. Simulation results from [34] indicate the severity of poor vaccine format stocking decisions: incorrect selection of single-dose vs. multi-dose format for the clinic's formulary can cost clinics between $8000 and $24,000 per vaccine, per year. For a clinic stocking 5 common vaccines, total costs of poor choice of single vs. multi-dose formats can exceed $65,000 per clinic, per year.

The interplay between shared consumption of single packages, rapid spoilage once opened, stringent consumer assortment demands, and high cost of wastage creates a difficult scheduling problem for the travel clinic administrator. With multiple vials of different vaccines open and deteriorating rapidly, and numerous patients each potentially requiring a different assortment of vaccines, determining the optimal scheduling of patients is non-trivial. In this paper, we show that traditional patient scheduling methods in travel vaccine clinics, such as first-in, first-out (FIFO), are sub-optimal and can lead to significant vaccine wastage. We propose and compare an integer programming model and a genetic algorithm solution procedure in Excel, that can significantly reduce a clinic's vaccine costs.

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It is possible to develop a patient scheduling DSS using a variety of software engines instead of Excel (e.g. MATLAB, LINDO, CPLEX), and some DSS designers will prefer one engine to another. Our objective was to design a decision support tool for clerical staff in a health care clinic using a familiar, affordable, and accessible software platform.

We begin with a discussion of related work in perishable inventory management, job shop scheduling, patient scheduling, and vaccine management and describe how our approach differs from past work. We then provide descriptions and experimental evaluations for the solution procedures we tested. Finally, we conclude with a discussion of recommendations, limitations, and areas for future research.

2. Related work

In this section, we briefly review traditional perishable inventory issuance policies, common parameters to perishable inventory models, standard performance measures for perishable inventory models, and historic application areas for these perishable inventory models. We review earlier work on job shop scheduling. We also look at prior operations research work in health care delivery, particularly pertaining to patient scheduling and vaccine management. Finally, we compare and contrast our work to the past literature.

2.1. Perishable inventory management

A substantive body of literature discusses the management of perishable inventory—see, for example Refs. [10,13,32,37–41]. Previous authors have considered both ordering policies for replenishing perishable inventory [27,41,43,50,55,64], and *issuance policies* for arranging or selling perishable inventory. The most commonly recommended issuance policy for perishable inventory is the age-based FIFO issuance policy, where the oldest unexpired product is issued first [48]. For inventory stockpiles with non-uniform deterioration, a quality-based issuance policy, SRSL (Shortest Remaining Shelf Life) is suggested [62]. For health-related perishables, such as blood, where patient needs vary in terms of urgency or inventory freshness, authors have recommended urgency or outsourcing classes [4] (where urgently needed stock is procured at extra expense from a 3rd party vendor, rather than stored in house) or freshness classes [21] to segregate stock and ensure availability of a compatible product for particularly ill or infirm patients. Inventory assortment decisions for varied perishable stock types have also been investigated [18].

Authors have considered a number of *parameters* that impact ordering and issuance decisions. Cost parameters include ordering cost, holding cost, outdates (e.g. disposal) cost, shortage costs, fixed and marginal production costs, and order backlogging costs. Typical external input parameters to perishable inventory models include order lead times, replenishment rates, consumption rates (most often regarded as Poisson distributed), shelf life, and stock deterioration rate, though some authors have introduced exotic parameters such as consumer patience [47]. Other controllable parameters have been considered, such as lot size [27], product pricing [13], and production or storage capacity [19].

To evaluate the efficacy of different models, authors typically measure profit, defined as expected sales revenues less all costs (enumerated earlier). Other *performance measures* include customer wait times or backlogged orders [1]; spoilage rate, lost sales rate, mean time between stock-outs, average inventory level on hand, distribution of age of items [33]; estimated effects on customer's store loyalty [25]; rate of outdatings, rate of high-cost special orders [4]; average age of inventory, probability of shortage, average number of items discarded per time period [6]; and expected quantity of any new order which will outdate [39].

Previous authors also have considered various *application areas* for perishable inventory management. Blood product management is a popular area of study [6,10,21,48,49], as is fresh food stock management [18,25,38,62], where authors have paid particular attention to seafood, meat, dairy, and bakery products. Some authors have even classed high-tech products with short productive or marketable life as perishables [68].

2.2. Job shop scheduling

The well-known job shop scheduling problem [11,61] is reminiscent of the sequencing difficulties encountered when scheduling patients for travel vaccination. In job shop scheduling, jobs (with machining needs) are assigned to machines. With patient scheduling, patients (with vaccination needs) are assigned to a nurse, or nurses, with limited capacity. In job shop scheduling, setup costs can be reduced and economies of scale can be achieved by grouping similar jobs by family [61]. In the vaccination problem, costs can be reduced by intelligent application of economically attractive multi-dose formulations. Notably, in the vaccination problem, a complication is added by the fact that multi-dose vials have limited shelf-life-once-opened. Further, since CDC injection safety recommendations discourage the sharing of open vials amongst multiple nurses, there is little opportunity to shift materials (drugs) amongst treatment stations (nurses). Finally, to minimize administration errors, a patient must receive all required vaccinations in a single sitting, rather than allowing a job to be split into multiple operations (individual vaccinations) spread over time. Nevertheless, techniques such as integer programming and genetic algorithms which have been shown to be effective in the job shop scheduling problem [11] are clearly pertinent to and useful for the travel vaccination problem.

2.3. Health care delivery: patient scheduling and vaccine management

Healthcare care delivery has been an important area of application for operations research techniques [5,20,57]. Important contributions have been made, in particular, for *patient scheduling*, such as surgical priority ranking [56], diagnostic facility scheduling [16,23,45], or inpatient bed assignment [58]. Typically, these approaches involve segmenting patients into urgency classes and giving priority to the more urgent cases. In the area of *vaccine management*, operations researchers have focused on a number of major issues. Formulary composition—selecting an optimal assortment of vaccines for the clinic's stockroom—has been the subject of much prior research [26,29,30,63]. The scheduling of catch up doses for patients that have missed multiple prior vaccines has also received some attention: for example, [17] implemented optimization technologies and a decision support tool to help healthcare practitioners schedule catch-up doses, taking into account minimum and maximum ages for administration, and time separation between doses. Various authors have employed operations research techniques to tackle the suppression of a single-disease pandemic, such as influenza, through the optimal selection or allocation of vaccines [12,52,54,67].

Finally, with the increasing availability of multi-dose vaccine formulations, attention has recently been paid to estimating the total economic impact of multi-dose versus single-dose formulations, by conducting sensitivity analysis assuming a range of multi-dose vial sizes, costs per dose, daily clinic arrival rates, and vaccine vial utilization rates [34]. This economic model informs formulary choice (whether to stock single-dose or multi-dose vaccine formats, and which multi-dose format, for various anticipated patient arrival rates) and vaccine packaging (how many doses per multi-dose vial, for vaccine manufacturing) based on average patient arrival rates, but does not provide suggestions for optimizing patient scheduling

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