ORIGINAL ARTICLE

Challenging the Throwaway Culture in Hospitals: Scheduling the Mix of Reusable and Single-Use Bronchoscopes

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ABSTRACT
Optimal material resource planning is crucial to run safe and cost-efficient hospital services. In this paper, we investigate a real problem in hospitals, motivated by an environmental and economically inefficient use of disposable, single-use, endoscopes. We develop a mathematical model and create a decision support tool to determine when reusable, multi-use, bronchoscopes should be sent for inspection including information to what extent single-use bronchoscopes can cover the remaining demand. Results show that the proposed approach can contain operational costs which consist of costs for buying single-use devices, inspection costs and reprocessing costs, i.e., sterilization of reusable devices. Our tool can assist hospitals to predict when reusable bronchoscopes should undergo inspection and whether the current inventory of reusable devices is sufficient to cover the demand. Finally, we evaluate the impact of variation in demand on total costs.

KEYWORDS
Decision Support Systems; Health Services; Mathematical Programming; Simulation; Sustainability

1. Introduction

Endoscopes are an important piece of hospital equipment. Usually, they are long, thin, and flexible tubes that have a light and a camera at one end. Endoscopes display images of the inside of the human body on a screen for a wide range of diagnostic procedures, such as gastroscopy to visualize the upper part of the digestive system. In this paper, we focus on better planning the use of bronchoscopes which are a specific type of endoscopes used to diagnose abnormalities in a patient's lung.

Since the first bronchoscopy performed in 1897 (Becker (2009)), the advances of the uses of bronchoscopes have had huge effects on the medical field. Safer bronchoscopy techniques have replaced many invasive or surgical techniques. This development has led to a reduction of surgical complications (Ong, Debiane, and Casal (2016)). A limiting application of this technology is the excessive cost of purchasing a reusable bronchoscope (Panchabhai and Mehta (2015)). The invention of the disposable or

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single-use bronchoscope filled this gap in technology, making it economically efficient if this type of device is rarely needed. While reusable devices need sterilization and decontamination after each use, reprocessing of disposable devices is unnecessary. The reprocessing of reusable bronchoscopes is a time-consuming procedure which follows high standards of infection control. Thus, running a safe service on reusable bronchoscopes can only be guaranteed if infection/contamination control measures are in place. In an international survey on procedures for reprocessing flexible bronchoscopes, 50% of respondents agreed that the need for regular bronchoscopes reprocessing training and education was a main concern (Kenters et al., 2018). The use of the disposable bronchoscopes eliminates the labour and economic cost of the reusable devices' reprocessing and inspection. However, due to the single-use nature of the devices, they are not always cost effective. The optical quality of reusable devices is often better when compared to the disposable technology (Châteauvieux et al., 2018). However, research gaps remain such as: If hospitals plan to carry out their bronchoscopies using reusable devices, what happens if some of the devices undergo scheduled inspection and is there a cost-efficient way to cover the demand with disposable or the remaining reusable device inventory?

1.1. Real Hospital Problems

Our research addresses a real-world problem in a major university hospital in Munich, Germany. The hospital has thirty-three individual departments which treats patients from Munich and the surrounding region. The problem, the inefficient use of disposable bronchoscopes, was discussed and defined with emergency medicine physicians, anaesthesiologists and intensive care physicians. The economic and environmental sustainability issues (Kleindorfer, Singhal, & Van Wassenhove, 2005) resulting from the inefficient use of disposable bronchoscopes create a major challenge for the hospital.

Environmental Issues Every year, the department for anaesthesiology and intensive care performs around 950 bronchoscopies. Before introducing our modelling approach and decision support tool to the hospital in 2015, disposable devices were the predominant bronchoscopy method. This led to an increased waste of single-use devices and packaging, leading to increased incineration. We assume a 6kg CO2 emission per kg of plastic and the service runs on disposable devices only. Assuming 1kg of plastic per disposable bronchoscope this would equal to a CO2 emission of 5.7 tons, not including the emissions for manufacturing and shipping all the disposable devices.

Economic and Process Inefficiency Disposable bronchoscopy devices can be economically inefficient compared to reusable devices. At the start of our collaboration, the hospital ran exclusively on disposable bronchoscopes. One issue was the ordering process and determining an optimal number of devices to stock. The €240 costs per disposable device challenged the hospital, reducing the contribution margin of each patients' Diagnosis Related Group (DRG) value, as German hospitals are reimbursed through DRG codes.

1.2. Contributions of the Paper

In this paper, we develop a mixed-integer program (MIP) to determine given a set of reusable bronchoscopes, when these bronchoscopes should undergo inspection and whether it is cost-efficient to cover the demand using disposable devices in a German university hospital. The proposed model is an extension of Edenharter, Gartner, and Pförringer (2017)'s strategic model which determined at which hospital size it is economically efficient to switch from disposable to reusable devices. Following multiple model extensions, a decision support tool to help managers make better decisions regarding how many disposable devices are required per week to cover the demand and when the inspection of reusable devices should take place was developed. The contribution of this study to the body of knowledge and practice is threefold:

(1) We expand on Edenharter et al. (2017)'s approach by introducing a discrete-time planning horizon, creating a schedule that informs decision makers when a disposable device is used and whether reusable devices have been used to satisfy weekly demand. This analytical model helps inform hospital's purchasing decisions and forecasts the weekly demand for the hospital's sterilization and decontamination unit.
(2) For each reusable device, we generate an inspection schedule. Depending on the inspection duration, it may be necessary to cover the demand using disposable devices, something that Edenharter et al. (2017)'s model ignores.
(3) We develop a decision support tool which can assist hospitals to solve this decision problem. A hospital's planning department can input parameters such as purchasing disposable devices and inspection costs of reusable devices. The number of available reusable devices, and weekly demand in the financial year can be parameterized. Our tool will then perform a cost analysis and determine the optimum number of disposable and reusable devices to use in each week. The manager can then procure the number of devices needed to meet the demand effectively and reduce costs for the hospital. In this way, the tool would help to run the hospital's intensive care unit (ICU) more efficiently.

We structure the remainder of our paper accordingly. In the next section, we provide an overview of related work followed by the presentation of our mathematical model and its implementation as a decision support tool. Then, we will evaluate variations in the stochastic demand and their impact on the actual costs accrued when planning with the results produced by our deterministic model. A discussion section will then highlight model limitations, its generalisability, and benefits for the hospital. Our paper closes with conclusions and potential areas of further research.

2. Related Work

Volland, Fügener, Schoenfelder, and Brunner (2017) provide a literature review on material logistics in hospitals. In accordance with their taxonomy, our planning approach has similarities with the following three streams: supply and procurement, inventory management, and distribution and scheduling decisions of sterile medical devices. In the remainder of this section, we will highlight the relevance and importance of the mentioned literature to the current research. Similarities and differences of our work with respect to publications in each of these three streams are stressed.

2.1. Supply and Procurement

Journal articles in which optimization approaches were used in the area of supply and procurement of goods in healthcare and which were categorized in Volland et al.

(2017)'s review are Hu and Schwarz (2011); Iacocca, Zhao, and Fein (2013); Rego, Claro, and de Sousa (2014); Ross and Jayaraman (2009), and Zhao, Xiong, Gavirneni, and Fein (2012). More recently, Edenharter et al. (2017) can be added to this category. In what follows, we examine the identified publications in greater detail and stress similarities and differences with our work.

Hu and Schwarz (2011) examine Group Purchasing Organizations (GPOs) in healthcare. They develop a mathematical model to determine under which circumstances the presence of GPOs lower prices. Group purchasing is important for a network of hospitals on the strategic level. However, our problem is a tactical planning problem to determine when reusable bronchoscopes are sent for inspection and how many disposable devices must be purchased on a weekly basis. As disposable bronchoscopes have a fixed price per item, group purchasing decisions are not decision relevant in our case.

Iacocca et al. (2013) focus on a multi-period production-inventory planning model with time varying parameters in the pharmaceutical industry. Their objective is profit maximization while considering manufacturer and the wholesaler inventory and ordering decisions. Not only is our focus on the consumer-side but, our modelling approach is different because the objective is not on maximizing production but minimizing costs.

Rego et al. (2014) develop a flexible approach for recommending the number, size, and composition of purchasing groups. They consider a set of hospitals willing to cooperate, while minimizing their shared supply chain costs. This problem has similarities with Hu and Schwarz (2011), but again, group purchasing orders are not relevant for our case.

Ross and Jayaraman (2009) focus on a health care purchasing problem for bundling new and refurbished products and propose a methodology for evaluating the trade-offs involved in bundling decisions for refurbished health care products. By exploiting useful properties of the problem structure, their results provide buyers with insights for examining and selecting suppliers who are willing to offer bundles of new and refurbished products. However, their model operates on a strategic level, whether it is beneficial to use refurbished vs. new products. Our approach is on a tactical level in which we want to find out when purchased reusable devices undergo inspection.

Zhao et al. (2012) formulate a multi-period stochastic inventory problem faced by a manufacturer and the distributor under a fee-for service contract. Our problem is different as we focus on the consumer side who needs to determine when to schedule inspection of bronchoscopy devices and how the remaining devices can cover the demand.

Most related to our work is Edenharter et al. (2017) who developed a strategic decision support tool to determine the optimal supply of reusable and disposable bronchoscopes. Their work builds on findings from Aïssou et al. (2013); Mager et al. (2018); Perbet et al. (2017); Tvede, Kristensen, and Nyhus-Andreasen (2012), and Gupta and Wang (2011) who indicated that when the number of bronchoscopies performed is small, total costs begin to favour disposable devices. Like our work, their decision support tool is based on a mathematical model. However, our model expands on their model by considering weekly variations in demand. Furthermore, our model provides feedback to the decision maker when the best period is to schedule reusable devices inspection.

2.2. Inventory Management

In addition to supply and procurement problems, Volland et al. (2017) reviewed optimization approaches applied to inventory management. Most publications in this field focus on a periodic inventory review policy rather than a continuous one, which is common hospital practice (Nicholson, Vakharia, & Erenguc, 2004). Our model focuses on point-of-use inventory. Optimization approaches for point-of-use problems and periodic inventory policy are, for example, Bijvank and Vis (2012), Little and Coughlan (2008), Rosales, Magazine, and Rao (2014), and Rosales, Magazine, and Rao (2015). In what follows, we examine these publications in greater detail and stress similarities and differences with our work.

Bijvank and Vis (2012) develop two types of exact models that deal with lost sales, periodic reviews with short lead times, and limited storage capacity. In a capacity model, the service level is maximized subject to a capacity restriction, and in a service model the required capacity is minimized subject to a service level restriction. The authors formulate approximation models applicable for any lost-sales inventory system (e.g., cost objective, no lead time restrictions). For the capacity model, they develop a simple inventory rule to set the reorder levels and order quantities.

Little and Coughlan (2008) develop a constraint-based model for determining optimal stock levels for all products at a storage location, with restrictions on space, delivery, and criticality of items considered. They validate their model on sterile and bulk items in a real-life setting. From a methodological point of view, our approach differs because we use mixed-integer programming and evaluate the inspection schedule using discrete-event simulation. As the ICU is a small space, we assume that we only have one storage location where the disposable and reusable devices are stored.

Rosales et al. (2014) evaluate a hybrid replenishment policy for medical supplies. It combines a low-cost periodic replenishment epoch with a high-cost continuous replenishment option to avoid costly stockouts. They develop a parameter search engine using simulation to optimize the long-run average cost per unit time.

Rosales et al. (2015) model an inventory system under periodic and continuous review. For periodic review, the authors show that the long-run average cost per unit time is quasi-convex, enabling a simple search for the optimal review cycle.

Our model allows for a periodic review policy since the user can use the model to predict the inventory required for a specified number of weeks, and then order accordingly. The user could adapt the use of the model depending on their hospital policy. While our model's objective function only considers costs relating to purchasing, reprocessing and inspection, other models also try to minimize variables such as the number of refills or stock on hand, considering inventory storage costs and constraints, for example, (Rosales et al., 2014) and (Rosales et al., 2015) which are closest to our approach in terms of inventory management.

2.3. Distribution and Scheduling

The literature on hospital resource planning tends not to take preventive maintenance of the medical equipment into account, it is assumed that the equipment is available throughout the planning horizon. Furthermore, in the distribution and scheduling literature specific issues are discussed, such as routing and scheduling problems of combined storage/delivery material management systems, e.g., mobile medicine delivery closets. Effective maintenance scheduling of hospital equipment is a practice which could improve service delivery (Mwanza & Mbohwa, 2015), and preventive maintenance can reduce costs and improve reliability (Marmolejo-Correa, Juarez-Valdivia, & Rodriguez-Navarro, 2016). Existing scheduling models, similarly, to our model, consider the inspection of the medical equipment (Ma, Chu, & Zuo, 2010; Schmidt, 2000; Wu, Dong, & Zheng, 2014). Lapierre and Ruiz (2007) propose an approach to schedule replenishments, purchasing activities, and supplier activities to avoid stockouts and respect resource availability. The authors formulate a mixed-integer non-linear scheduling problem that balances employees' workload. They develop a tabu search meta-heuristic algorithm for solving the problem.

The MIP model proposed in this paper can be placed into and differentiated from the literature as follows. Our approach extends (Edenharter et al., 2017)'s strategic problem by discretizing the planning horizon. The model provides information when reusable bronchoscopes must undergo inspection and the decision support tool provides feedback, when and how many disposable devices are used. Furthermore, (Lapierre & Ruiz, 2007) is related because they developed a mixed-integer model for purchasing activities. In contrast to our model, workload constraints are not decision relevant.

3. Mathematical Model

In what follows, we will introduce the parameters of our MIP, the decision variables, objective function, and constraints. An example cost analysis is given in the supplementary material. A summary of all parameters and decision variables is provided in Table 1.

3.1. Sets, Indices and Parameters

We present the parameters in the following parts: i) devices, planning horizon and demand, ii) cost parameters and iii) other operational parameters.

3.1.1. Devices, Planning Horizon and Demand

We introduce $\mathcal{I}$ as the set of reusable devices and $\mathcal{W}$ denotes the set of weeks to schedule the use of disposable and the inspection of the reusable devices. Furthermore, let b_w be the demand in week $w \in \mathcal{W}$. We established that the set of weeks should be 8-12 weeks due to: 1) seasonal patterns in demand which makes it hard to forecast demand and 2) tactical financial planning is often broken down into quarters of a year.

3.1.2. Cost Parameters

We introduce the following three cost terms: $c^{disposable}$ denote the purchasing cost of a disposable device, $c^{inspection}$ is the inspection cost of a reusable device and c^{rep} is the reprocessing costs of a reusable device. Mouritsen, Ehlers, Kovaleva, Ahmad, and El-Boghdadly (2020) provide example cost parameters.

3.1.3. Other Operational Parameters

Let $k_i \in \mathbb{N}$ denote the number of remaining uses for device $i \in \mathcal{I}$ that recently returned from inspection. Furthermore, let $k_i^{start} \in \mathbb{N}$ be the number of uses remaining on a reusable device $i \in \mathcal{I}$ at week 1. We introduce $n^{reusable}$ as the maximum number of bronchoscopies that can be carried out in a week, with both technologies. Furthermore, let O denote the inspection duration for a reusable device and let $W^{\max}$ be the

Table 1. Sets, indices, constants, and decision variables.

Parameter	Description
$\mathcal{I}$	Set of reusable devices
$\mathcal{W}$	Set of weeks in a financial year
b_w	Demand in week $w \in \mathcal{W}$
$c^{disposable}$	Purchasing cost of a disposable device
$c^{inspection}$	Inspection cost of a reusable device
c^{rep}	Reprocessing costs of a reusable device
$k_i \in \mathbb{N}$	Number of remaining uses for reusable $i \in \mathcal{I}$ that just came back from inspection
$k_i^{start} \in \mathbb{N}$	Number of remaining uses on a reusable device $i \in \mathcal{I}$ at week 1
$n^{reusable}$	Maximum number of bronchoscopies that can be carried out in a week, for both technologies (reusable and disposable)
O	Inspection duration for a reusable device (in weeks)
$W^{\max}$	Maximum number of weeks a reusable device can be used without inspection

Decision variable	Description
$q_{i,w} \in \mathbb{N}$	Number of actual uses of reusable device $i \in \mathcal{I}$ in week $w \in \mathcal{W}$
$x_w^{disposable} \in \mathbb{N}$	Number of disposable devices used in week $w \in \mathcal{W}$
$x_{i,w}^{reusable,available}$	$= 1$ if reusable device $i \in \mathcal{I}$ is available in week $w \in \mathcal{W}$, 0 otherwise
$x_{i,w}^{start}$	$= 1$ if the inspection for reusable device $i \in \mathcal{I}$ starts at the beginning of week $w \in \mathcal{W}$, 0 otherwise
$x_{i,w}^{stop}$	$= 1$ if the inspection for reusable device $i \in \mathcal{I}$ stops at the beginning of week $w \in \mathcal{W}$, 0 otherwise

maximum number of weeks device i can operate without inspection. Naturally, $W^{\max}$ cannot exceed the planning horizon, so we have to restrict $W^{\max} \leq |\mathcal{W}|$.

3.2. Decision Variables

We introduce $q_{i,w} \in \mathbb{N}$ which is the number of actual uses of reusable device $i \in \mathcal{I}$ in week $w \in \mathcal{W}$. Next, let $x_w^{disposable} \in \mathbb{N}$ denote the number of disposable devices used in week $w \in \mathcal{W}$. Binary variables $x_{i,w}^{reusable,available} = 1$ if reusable device $i \in \mathcal{I}$ is available in week $w \in \mathcal{W}$ and 0 otherwise. We introduce another binary variable $x_{i,w}^{start} = 1$ if the inspection for reusable device $i \in \mathcal{I}$ starts at the beginning of week $w \in \mathcal{W}$, 0 otherwise. Finally, let binary variables $x_{i,w}^{stop} = 1$ if the inspection for reusable device $i \in \mathcal{I}$ stops at the beginning of week $w \in \mathcal{W}$, 0 otherwise.

3.3. Objective Function

The objective function (1) minimizes the sum of the total cost of purchasing the disposable devices, the total cost of inspection of reusable devices and total cost of reprocessing the reusable devices.

$$\text{Minimize} \quad z = \sum_{w \in \mathcal{W}} c^{disposable} \cdot x_w^{disposable} + \sum_{i \in \mathcal{I}} \sum_{w \in \mathcal{W}} c^{inspection} \cdot x_{i,w}^{start} + \sum_{i \in \mathcal{I}} \sum_{w \in \mathcal{W}} c^{rep} \cdot q_{i,w} \quad (1)$$

3.4. Constraints

Constraint (2) ensures that an inspection will take place on a reusable device if the number of remaining uses before an inspection reduces to zero. Note that we use the convention that if $x_{i,w}^{stop}$ variables are 1, then the device is available in the beginning of week w and throughout that week but not in the entire week $w-1$. We could also interpret it as the device is back from inspection and fully available in week w. To avoid confusion, we provide an example in the Supplementary Material.

$$k_i^{start} - \sum_{\tau=1}^{w} q_{i,\tau} + \sum_{\tau=1}^{w} x_{i,\tau}^{start} \cdot k_i \geq 0 \qquad \forall i \in \mathcal{I}, w \in \mathcal{W} \quad (2)$$

Constraint (3) ensures that the inspection for reusable devices lasts for the inspection duration O. However, if the device does not go under inspection, the constraint is not binding which is why we multiply it with $\sum_{w \in \mathcal{W}} x_{i,w}^{start}$. Furthermore, by multiplying with the index w within the term $\sum_{w \in \mathcal{W}} w \cdot x_{i,w}^{stop}$, this gives us the week in which the inspection stops. For example if $x_{1,7}^{stop} = 1$ (see Table 1 in the Supplementary Material), the result is $1 \cdot 0 + 2 \cdot 0 + 3 \cdot 0 + 4 \cdot 0 + 5 \cdot 0 + 6 \cdot 0 + 7 \cdot 1 + 8 \cdot 0 = 7$. This concept is similar to the one used in event-based job shop scheduling and has been applied in patient scheduling (Gartner and Kolisch (2014)).

$$\sum_{w \in \mathcal{W}} w \cdot x_{i,w}^{stop} - \sum_{w \in \mathcal{W}} w \cdot x_{i,w}^{start} = \sum_{w \in \mathcal{W}} x_{i,w}^{start} \cdot O \qquad \forall i \in \mathcal{I} \quad (3)$$

Constraint (4) ensures that a reusable device is not available if it is in inspection and is available if it is not in inspection. The part in the bracket indicates whether or not device i is under inspection in week w. Gartner and Padman (2020) used this modelling concept previously for modelling patients' lengths of stay on beds for multiple days.

$$x_{i,w}^{reusable,available} + \left(\sum_{\tau=1}^{w} x_{i,\tau}^{start} - \sum_{\tau=1}^{w} x_{i,\tau}^{stop} \right) = 1 \qquad \forall i \in \mathcal{I}, w \in \mathcal{W} \quad (4)$$

Constraint (5) ensures that the total number of reusable and disposable devices used in week w meets the demand for that week.

$$\sum_{i \in I} q_{i,w} + x_w^{disposable} \geq b_w \qquad \forall w \in \mathcal{W} \quad (5)$$

Constraint (6) ensures that if a reusable device is used in a week, it must be available.

The parameter for the big M formulation can be set to the upper bound $M = n^{reusable}$.

$$q_{i,w} - M \cdot x_{i,w}^{reusable,available} \leq 0 \qquad \forall i \in \mathcal{I}, w \in \mathcal{W} \tag{6}$$

Constraints (7)–(8) ensure that there is at most 1 inspection in the planning horizon.

$$\sum_{w=1}^{\mathcal{W}} x_{i,w}^{stop} \leq 1 \qquad \forall i \in \mathcal{I} \tag{7}$$

$$\sum_{w=1}^{\mathcal{W}} x_{i,w}^{start} \leq 1 \qquad \forall i \in \mathcal{I} \tag{8}$$

Sometimes, the inspection of a device is not optional but mandatory. In this case, we must ensure that the inspection is scheduled well before the end of the planning horizon which is ensured by constraints (9).

$$\sum_{w=1}^{W^{\max}-O^{\min}} x_{i,w}^{start} = 1 \qquad \forall i \in \mathcal{I} \tag{9}$$

(10)–(12) are the decision variables and their domains. (10) are bounded because of hospitals' sterilisation and decontamination capacity.

$$0 \leq q_{i,w} \leq n^{reusable} \qquad \forall i \in \mathcal{I}, w \in \mathcal{W} \tag{10}$$

$$x_{i,w}^{reusable,available}, x_{i,w}^{start}, \text{and } x_{i,w}^{stop} \in \{0,1\} \qquad \forall i \in \mathcal{I}, w \in \mathcal{W} \tag{11}$$

$$x_{w}^{disposable} \in \mathbb{N} \qquad \forall w \in \mathcal{W} \tag{12}$$

The model creates an inspection schedule for each reusable device by keeping a usage count since its last inspection and ensures that inspection occurs before the number of remaining uses drops to zero. Using this inspection schedule, the model can determine which reusable devices are available in each week.

The entire model can be summarized using (13)–(24):

$$\text{Minimize} \quad z = \sum_{w \in \mathcal{W}} c^{disposable} \cdot x_{w}^{disposable} + \sum_{i \in \mathcal{I}} \sum_{w \in \mathcal{W}} c^{inspection} \cdot x_{i,w}^{start} + \sum_{i \in \mathcal{I}} \sum_{w \in \mathcal{W}} c^{rep} \cdot q_{i,w} \tag{13}$$

subject to

$$k_i^{start} - \sum_{\tau=1}^{w} q_{i,\tau} + \sum_{\tau=1}^{w} x_{i,\tau}^{start} \cdot k_i \geq 0 \qquad \forall i \in \mathcal{I}, w \in \mathcal{W} \qquad (14)$$

$$\sum_{w \in \mathcal{W}} w \cdot x_{i,w}^{stop} - \sum_{w \in \mathcal{W}} w \cdot x_{i,w}^{start} \geq \sum_{w \in \mathcal{W}} x_{i,w}^{start} \cdot O \qquad \forall i \in \mathcal{I} \qquad (15)$$

$$x_{i,w}^{reusable,available} + \left(\sum_{\tau=1}^{w} x_{i,\tau}^{start} - \sum_{\tau=1}^{w} x_{i,\tau}^{stop} \right) = 1 \qquad \forall i \in \mathcal{I}, w \in \mathcal{W} \qquad (16)$$

$$\sum_{i \in I} q_{i,w} + x_w^{disposable} \geq b_w \qquad \forall w \in \mathcal{W} \qquad (17)$$

$$q_{i,w} - M \cdot x_{i,w}^{reusable,available} \leq 0 \qquad \forall i \in \mathcal{I}, w \in \mathcal{W} \qquad (18)$$

$$\sum_{w=1}^{\mathcal{W}} x_{i,w}^{stop} \leq 1 \qquad \forall i \in \mathcal{I} \qquad (19)$$

$$\sum_{w=1}^{\mathcal{W}} x_{i,w}^{start} \leq 1 \qquad \forall i \in \mathcal{I} \qquad (20)$$

$$\sum_{w=1}^{W^{\max}-O^{\min}} x_{i,w}^{start} = 1 \qquad \forall i \in \mathcal{I} \qquad (21)$$

$$0 \leq q_{i,w} \leq n^{reusable} \qquad \forall i \in \mathcal{I}, w \in \mathcal{W} \qquad (22)$$

$$x_{i,w}^{reusable,available}, x_{i,w}^{start}, x_{i,w}^{stop} \in \{0,1\} \qquad \forall i \in \mathcal{I}, w \in \mathcal{W} \qquad (23)$$

$$x_w^{disposable} \in \mathbb{N} \qquad \forall w \in \mathcal{W} \qquad (24)$$

4. Decision Support Tool and its Benefits for the Hospital

Before we developed the model, we evaluated the usability of the tool presented by Edenharter et al. (2017) in UK's National Health Service (NHS). Since there was no option to use a commercial solver, we implemented Edenharter et al.'s model in the GNU Linear Programming Kit (GLPK) (Makhorin (2018)). Subsequently, we evaluated the usability of the decision support tool in practice with decision makers. The feedback received was that the tool, preferably in Microsoft Excel, should cover each reusable device independently and, it should split the planning horizon into at least quarters to assist device procurement decisions.

With this feedback, we developed the mathematical model, in an iterative process. We implemented the model as a decision support tool in Microsoft Excel. As the classical Microsoft Excel solver can only manage a limited number of decision variables and constraints, we used OpenSolver (Mason, 2012) and COIN-OR (Lougee-Heimer, 2003) as a back-end to solve the mathematical model. Figure 1 shows the decision support tool which includes an 8-week planning horizon and 3 reusable devices. All parameters are customisable depending on characteristics of the hospital using the tool. Figure 1 also reveals that the user can input the specific costs of buying disposable devices, and inspection and reprocessing reusable devices.

The user inputs, for example, the maximum weekly number of bronchoscopies per-

Figure 1. The user can input the cost parameters for disposable devices as well as the inspection and reprocessing costs for reusable devices (see Sohrt et al. (2019) for example figures). Other parameters such as the expected demand can be updated. Note that costs for purchasing reusable devices cannot be parameterised as this is a tactical decision-level tool which assumes that the decision maker would have used (Edenharter et al., 2017)'s approach to determine the number of reusable devices.

Decision Support Tool

Costs									
Cost of buying 1 disposable device		120							
Cost of inspection of each reusable device		1,000							
Cost of reprocessing each reusable device		100							
Info									
Max no. of broncoscopies /resuable device /week		7							
Inspection duration for reusable device (weeks)		2							
Quality duration after inspection (uses)		100							
Max weeks device can be used without inspection		6							
	Total weeks:	8							
	Week	1	2	3	4	5	6	7	8
How many devices are required in a given week									
Devices		50	21	30	29	18	23	35	31

formed per reusable device, limited due to reprocessing time. The user specifies the number of weeks without inspection per device. Finally, they input the inspection duration and the number of uses after the inspection the device can perform. With all the parameters input, the decision support tool then interacts with COIN-OR and produces the inspection schedule with cost information.

Figure 2 shows which reusable devices are available in each week. It displays a table of the "Remaining uses of reusable device", a variable showing the number of uses left on each reusable device before inspection is required, which the model ensures does not drop below zero for each device. Our example in the Supplement Material explains the constraint used on this table. The remaining uses for each device "At start of week 1" should be input by the user depending on the starting condition of each device.

Figure 2. Reusable bronchoscopes availability and number of remaining uses.

Which reusable devices are available in a given week (Yes = 1, No = 0)										
Reusable Device		1	1	1	1	1	0	0	1	1
		2	0	0	1	1	1	1	1	1
		3	1	0	0	1	1	1	1	1
	Total		2	1	2	3	2	2	3	3
Remaining uses of reusable device before the inspection	**At start of week 1:**									
Device 1		30	23	16	9	2				
Device 2		0								
Device 3		14	7							

Figure 3 shows the inspection schedule. During inspection a device is not available, and the model will not schedule it for use. The model devised inspection schedule for each device are displayed using start/stop variables and the "Device in Inspection" table shows for each reusable device whether it is in inspection or not each week.

Finally, in Figure 4 the proposed schedule reveals which devices to use each week to minimize costs. In this example, we can see that the model recommends using

Figure 3. Reusable bronchoscopes inspection schedules.

Inspection Schedule	Week:	1	2	3	4	5	6	7	8
Inspection start device 1		0	0	0	0	1	0	0	0
Inspection stop device 1		0	0	0	0	0	0	1	0
Inspection start device 2		1	0	0	0	0	0	0	0
Inspection stop device 2		0	0	1	0	0	0	0	0
Inspection start device 3		0	1	0	0	0	0	0	0
Inspection stop device 3		0	0	0	1	0	0	0	0
	Total inspection starts	1	1	0	0	1	0	0	0
	Total inspection stops	0	0	1	1	0	0	1	0
Device in Inspection (Yes = 1, No = 0)									
Device 1		0	0	0	0	1	1	0	0
Device 2		1	1	0	0	0	0	0	0
Device 3		0	1	1	0	0	0	0	0

disposable devices in addition to reusable devices to satisfy the demand.

Figure 4. The tool provides the device schedule. Cost types by device type and weeks are presented.

Number of times reusable device is used in a given week									
Reusable Device	1	7	7	7	7	0	0	7	7
	2	0	0	7	7	7	7	7	7
	3	7	0	0	7	7	7	7	7
	Total	14	7	14	21	14	14	21	21
How many disposable devices are used in a given week									
Disposable Devices		36	14	16	8	4	9	14	10
Costs in a given week									
Total cost of buying disposable devices		4320	1680	1920	960	480	1080	1680	1200
Total cost of reprocessing of reusable devices		1400	700	1400	2100	1400	1400	2100	2100
Total cost of inspection of reusable devices		1000	1000	0	0	1000	0	0	0
	Total	6720	3380	3320	3060	2880	2480	3780	3300
Total Cost (over 8 weeks)	28920								

5. Demand Variation Results

To study the impact of demand variation on total costs, we developed a discrete-event simulation (DES) model using Simul8 (Mc Gregor and Cain (2004)).

5.1. Simulation Model Parameters

The model structure is shown in the Supplementary Material and in the following, we highlight how we set up the demand and the capacities in the simulation model. We used Simul8's trial calculator for the Uniform distribution and Log-normal distribution setting. Our experiments revealed that a maximum of 3,013 runs were required to determine a 99% confidence interval for the number of uses broken down by device types.

5.1.1. Demand

To set up the inter-arrival time parameter, we used a Uniform distribution with a lower bound of 0 and an upper bound of $2 \cdot (1/29.625 \text{ weeks})$ leading to an expected value of $1/29.625$ weeks between two consecutive arrivals. This figure is obtained by averaging the 8 weeks demand figures from Figure 1.

To add variation, we used a Log-normal distribution with an expected value of $1/29.625$ weeks and standard deviation of 0.1. While the activity which represents the disposable item use in the Simul8 has a zero duration because these items are available straight away, for the reusable devices we assumed 1 day reprocessing time.

5.1.2. Reusable Devices

To set up the reusable device capacities in the simulation model, we incorporated the week-dependent schedule from Figure 2 using the resource scheduler. Furthermore, the activity representing the use of the reusable devices would only pull in demand if there is no queue. In other words, disposable devices would be used if the reusable devices are all busy.

5.2. Simulation Results

Table 2 shows the results of our sensitivity analysis when running the DES model using the data from Figure 4 and the aforementioned demand of, on average, 29.625 bronchoscopies are performed each week. The table includes lower, average, and upper confidence interval limits on the number of uses of each device technology. We also provide the cost figures using data from Figure 1 and incorporating the number of uses per device technology.

Table 2. Simulation model results with uniformly and log-normal distributed demand and average (lower-upper 99% confidence interval)

	Demand distribution		
	$U(0,\frac{2}{29.625})$	Log-normal $(\frac{1}{29.625},0.1)$	Log-normal $(\frac{1}{29.625},0.2)$
Disposable uses	132.72 (131.54-133.90)	163.01 (161.38-164.64)	185.15 (183.30-187.00)
Reusable uses	100.65 (99.65-101.66)	74.88 (74.23-75.54)	62.98 (62.42-63.54)
Costs (in €)	28,991 (28,750 - 29,234)	30,049 (29,789-30,311)	31,516 (31,238-31,794)

The figures reveal that in the Uniformly distributed demand case, 132.72 bronchoscopies were performed by disposable devices while 100.65 bronchoscopies were carried out using a reusable device(s). In contrast, in the Log-normal case where demand variation is higher, 163.01 disposable devices are used which is an increase by almost 62%. At the same time, reusable devices are used only 74.88 times which is a drop by approximately 25%. Furthermore, the costs are higher in the Uniformly distributed demand case which are €28,991 as compared to the figure in the deterministic model which was €28,920, see Figure 4. Although this is only a 0.2% difference, it increases substantially to €30,049 and €31,516 if demand variation is introduced. This equals to an almost 4 and 8% increase for the 0.1 and 0.2 cases, respectively. Note also, that, in the Log-normal case the €28,920 is below the lower confidence interval bound. As a conclusion, this highlights the usefulness of taking variation in demand into account when planning the optimal mix of reusable and disposable devices.

6. Discussion and Limitations

6.1. Benefit of the Proposed Solution for the Hospital

Since using the proposed model and the decision support tool, the hospital has been able to invest in reusable devices and drastically reduce the use of disposable devices. The hospital has reported an annual reduction in the environmental footprint, measured by CO_2 emission to be six tons/year. The hospital disposed of 950 disposable bronchoscopes/year before implementing the model. The hospital has modified their inventory policy substantially reducing the number of disposable bronchoscopes kept in stock. Hence, this policy has resulted in actual substantial environmental and economic savings.

The previous policy to stock disposable devices cost €228,000. In contrast, the new policy to use reusable devices has led to a purchasing and reprocessing cost of €45,650. This translates into an actual saving of €182,350/year thanks to the proposed approach. Note that these figures do not include the staff involved in the inefficient ordering process. However, the costs include washing and inspection but also costs for reusable devices which is a decision made by Edenharter et al. (2017)'s approach.

6.2. Model Limitations

Our model schedules at most one inspection for each reusable device over the planning horizon. To overcome this limitation, the inspection start and stop variables could be adjusted (first, second, third inspection etc.).

We assume that the activity prescribed by the decisions is directly proportional to the costs. This means that we ignore, for example, that the seller of bronchoscopes might have a free of charge first inspection and then charge for subsequent inspections. At present, there is no economies of scale when purchasing bundles of disposable devices nor processing batches of reusable devices.

The model does not consider the storage capacity for the disposable devices. We assume that there is no maximum number of devices or holding costs for the disposable devices. We assume weekly purchases of devices and there are enough devices available, which may not always be true due to storage constraints. Using a production scheduling modelling approach may remedy this assumption.

We assumed that the hospital's demand prediction model is dependable. Naturally, there is an upper bound of demand due to the size of the ICU which dictates the number of bronchoscopies required each week. However, to build a more accurate model and decision support tool, stochastic demand should be considered. This would mean that the hospital has a safety stock of disposable devices in case of emergency, and the model would inform the decision maker about the size of the stock.

6.3. Generalizability of our Approach

Our model and decision support tool might be useful to plan the inspection of other types of endoscopes (e.g., gastroscopes). Consequently, our decision support tool can link information about multiple devices to schedule inspection ahead of time and avoid delayed surgeries. However, given the type of the device the model might need to be adapted to allow for multiple inspection activities. Our model may be generalisable to schedule decisions for the inspection of vehicle fleets such as ambulances or vans that collect specimens. Usually, vehicles display the number of days/miles left before the next service. Information about the expected use of vehicles paired with our decision support tool can help better plan scheduled services. It is helpful to know whether a replacement vehicle is needed during an inspection period.

6.4. *Usability of the Planning Approach in Practise*

Our model deals with a tactical planning problem, not a strategic one. When the setup cost of a reusable system of the bronchoscopy is included verse a system with purely disposable devices, the decision problem becomes richer and could provide more insights to the management team. On the other hand, under the Covid-19 threat, patients/doctors may have put different weights on the reusable and disposable devices. This might affect how decision makers adopt the results of the model in practise.

7. Conclusions, Lessons Learned, and Further Research

In what follows, we summarise the development of our approach and lessons learned when transitioning from a policy of using disposable bronchoscopes only, towards mixing the two technologies in practice. The section closes with potential areas of further research.

7.1. *Summary*

We have presented an analytical model for scheduling the mix of reusable and disposable bronchoscopes. The model has two significant extensions of Edenharter et al. (2017)'s strategic problem: the presented MIP discretizes the planning horizon into weeks allowing decision makers to plan the availability of disposable and reusable bronchoscopes. The model considers service intervals and durations of reusable devices providing information when reusable bronchoscopes are unavailable, which results in some cases where emergency physicians needing to perform a diagnostic procedure will use disposable devices. Our objective function extends Edenharter et al. (2017) because it considers temporal information about procuring disposable devices, the costs of reprocessing and inspection costs of reusable devices.

Due to feedback, we implemented the mathematical model in a more user-friendly decision support tool which uses OpenSolver (Mason, 2012) and the COIN-OR (Lougee-Heimer, 2003) open-source solver as a back-end. The application of our mathematical model in the collaborating university hospital revealed significant cost savings by using our tactical decision support system.

7.2. *Lessons Learned*

Before the introduction of reusable bronchoscopes, there were concerns when disposing of a bronchoscope after one use. Therefore, the new system, using reusable bronchoscopes had significant impact on the stock policy for disposal bronchoscopes in the hospital. This lesson was also transferable to other settings, for example, when using disposal surgical scissors. For most nurses and doctors, it requires a major effort to dispose single-use items after one use. So, the results of the study were not limited to financial and environmental improvement but also a game changer in terms of the reduction of single-use items. The introduction of reusable bronchoscopes was welcomed and alleviated the concerns of the staff. Additionally, the performance of disposable bronchoscopes was lower than the reusable devices. Doctors prefer to use high quality equipment to gain the best results possible. In conclusion, we learned that the model helped to supply the medical team and make a more informed choice of which equipment type to use and when.

7.3. Behaviour Change Beyond the Model

The results of our mathematical modelling had significant impact on the stock policy for bronchoscopes in the hospital. It has been reported that the acceptance of any single-use items (not only bronchoscopes) becomes reduced. This is true, in particular, when the single-use items become more and more costly and valuable. This phenomenon is known in the literature as "behaviour beyond the model", see Kunc, Malpass, and White (2016) and White, Kunc, Burger, and Malpass (2020). This demonstrates that our modelling has provided deeper insight into the throwaway culture issues and we have shown that our results are transferable to other situations (Eden and Ackermann (2006); Laughlin, Bonner, and Miner (2002)). Almost every time when disposing single-use items, between nurses and doctors there was a discussion why single-use items are used. So the results of our study revealed a behavioural shift from single-use items towards the use of reusable items.

7.4. Identify new Directions for Further Research

Future work will expand on the following three streams: using Design Science principles to improve the usability and acceptability of our decision support system. We will apply our tool in another healthcare system. Finally, another interesting avenue of future research is to link our mathematical model with forecasting techniques.

7.4.1. Evaluation of the Usability and Acceptability of our Decision Support Tool

Using the Think Aloud Protocol (Singhee et al., 2016) with senior managers, we will evaluate the usability and acceptability of our decision support tool. Although, we have qualitative feedback from our partners at the university hospital in Munich, it would be useful to develop a structured Design Science approach to measure the actual acceptance of the system. The managers' feedback will then be incorporated into an updated version of the tool.

7.4.2. Use in Other Healthcare Systems

In future work, we will evaluate the use in UK's NHS, with existing partners who have demonstrated significant interest in using the decision support tool.

7.4.3. Expanding on Linking Predictive and Prescriptive Modelling

The mathematical model relies on weekly-based demand forecasts. Given that the ICU is very busy, we assume that we will not run into challenges such as intermittent demand which would need different modelling and demand forecasting approaches. However, if we applied of our model to other use cases, linking forecasting approaches with discrete optimization models could be another area of future research.

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