Rohini	4 Color Fig(s): F1-4	02/2/17	20:00	Art: AAJ-D-16-01609

Decision Support for the Capacity Management of Bronchoscopy Devices: Optimizing the Cost-Efficient Mix of Reusable and Single-Use Devices Through Mathematical Modeling

Günther M. Edenharter, MD,* Daniel Gartner, MS,† and Dominik Pförringer, MD‡

BACKGROUND: Increasing costs of material resources challenge hospitals to stay profitable. Particularly in anesthesia departments and intensive care units, bronchoscopes are used for various indications. Inefficient management of single- and multiple-use systems can influence the hospitals' material costs substantially. Using mathematical modeling, we developed a strategic decision support tool to determine the optimum mix of disposable and reusable bronchoscopy devices in the setting of an intensive care unit.
METHODS: A mathematical model with the objective to minimize costs in relation to demand constraints for bronchoscopy devices was formulated. The stochastic model decides whether single-use, multi-use, or a strategically chosen mix of both device types should be used. A decision support tool was developed in which parameters for uncertain demand such as mean, standard deviation, and a reliability parameter can be inserted. Furthermore, reprocessing costs per procedure, procurement, and maintenance costs for devices can be parameterized.
RESULTS: Our experiments show for which demand pattern and reliability measure, it is efficient to only use reusable or disposable devices and under which circumstances the combination of both device types is beneficial.
CONCLUSIONS: To determine the optimum mix of single-use and reusable bronchoscopy devices effectively and efficiently, managers can enter their hospital-specific parameters such as demand and prices into the decision support tool.
The software can be downloaded at: https://github.com/drdanielgartner/bronchomix/. (Anesth Analg 2017;XXX:00–00)

In the long history of bronchoscopy, the optical tool for the procedure always has been and still is a very precious device. Its quality and state of care codetermines the result of the examination. Therefore, the device has to be handled with care. However, conventional multiple-use products require substantial expenses for buying, cleaning, sterilization, and general maintenance and repair.

In 1990 Mehta et al[1] were the first to point out the high costs of repair and maintenance concerning bronchoscopies. Since then, those expenses have further increased and are unlikely to decrease in the future.[2] In the last few years, single-use devices have been developed and already are used in many clinical settings. Those systems incur only the purchase price and are limited to just one single examination. No expenses for cleaning, maintenance, and repair arise, and the risk of cross-contamination[3] can be minimized. They also offer the benefit of a virtually unlimited parallel use, whereas reusable products limit physicians to linear use, defined as one procedure following the other, interrupted by cleansing and rearming times.

In addition to requirements on technical properties of the device, frequency and urgency of bronchoscopy examinations may influence the choices of managers and physicians. A direct comparison of the potential advantages and disadvantages of the 2 systems focusing on costs can help hospitals in their procurement decisions. So far, some studies on costs for reusable bronchoscopes have focused on repair and maintenance in a pulmonology setting.[1,4,5] Other studies compare costs for reusable with disposable devices for the purpose of intubation.[2,6–8] So far, no generalizable model had existed or was readily available to compare cost structures for the 2 types of devices or to support the decision making toward an optimum number of reusable and disposable bronchoscopes on a strategic level. Therefore, goal of our study is 2-fold: First, we develop a model allowing physicians and hospital managers to calculate the economically ideal setup for uncertain demand. Linking our model with a graphical user interface-based decision support tool is the second goal of our study.

METHODS

In this study, the problem of planning the mix of single-use and reusable bronchoscopy devices was approached by the use of a mathematical model that is presented in the Technical Appendix. It can be stated as follows: Determine

From the *Klinikum rechts der Isar, Technische Universität München, Klinik für Anaesthesiologie, München, Germany; †School of Mathematics, Cardiff University, United Kingdom; and ‡Klinikum rechts der Isar, Technische Universität München, Klinik und Poliklinik für Unfallchirurgie, München, Germany.

Accepted for publication October 4, 2016.

Funding: None.

The authors declare no conflicts of interest.

Günther M. Edenharter and Dominik Pförringer equally contributed to this article.

Reprints will not be available from the authors.

Address correspondence to Dominik Pförringer, MD, Klinikum rechts der Isar, Technische Universität München, Klinik und Poliklinik für Unfallchirurgie, München, Germany. Address e-mail to Dominik.Pfoerringer@mri.tum.de.

DOI: 10.1213/ANE.0000000000001729

the cost-efficient mix of reusable and disposable bronchoscopes subject to uncertain demand.

The established model takes into account the following cost terms:

- costs for buying a new disposable device,
- costs for buying a new reusable device, and
- reprocessing costs (once a reusable device was used, it has to be reprocessed).

In addition, each reusable device can cover a certain amount of demand during its lifetime.

Objective Function and Constraints

The objective function of the model minimizes 3 terms. First, the costs of disposable devices are minimized when the remainder of the objective function focuses on the reusable devices. In the second term of the objective function, costs associated with buying reusable bronchoscopes are minimized. The costs of reprocessing reusable devices are minimized in the third term of the objective function. The constraints of the model ensure that uncertain demand is covered by a user-defined reliability measure.

Bronchomix—A Decision Support Tool to Calculate the Optimal Mix of Bronchoscopes

We developed a Java-based decision support tool that simplifies the process to determine the optimal mix of bronchoscopes given information about demand, costs, and the decision maker's reliability measure. The decision maker can plug cost and demand information into the decision support tool (Figures 1 and 2), and the output gives the optimal mix of bronchoscopes. The tool and installation directions are available at https://github.com/drdanielgartner/bronchomix.

The study is a mathematical model without personal patient data. Therefore, approval from an institutional review board is not necessary.

RESULTS

In our experimental analysis section, we describe the parameters that we used to carry out in our study, followed by a presentation of our results.

Demand, Reprocessing Times, and Costs

Table 1 provides an overview of realistic cost parameters and expected demand. Both were obtained from the Department of Anesthesia and Intensive Care of the Klinikum rechts der Isar, Medical Center of the Technical University of Munich, Germany.

Cost Analysis Results

Figure 1 shows the solution with a Gaussian distributed demand, mean, μ = 950 standard deviation σ = 50, and reliability measure α = 0.95. The cost parameters are set according to Table 1. Figure 1 reveals that the solution of the program decides to buy 2 reusable and 33 disposable bronchoscopes.

Figure 2 shows another example with the same cost values and distribution parameters but with a reliability measure of α = 0.95. The figures reveal that now, the optimal solution

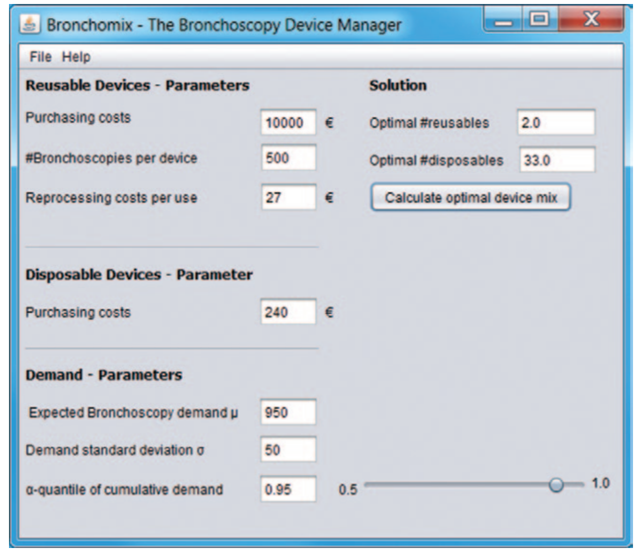

Figure 1. Optimal solution for μ = 950, standard deviation of σ = 50 bronchoscopies, and reliability measure α = 0.95.

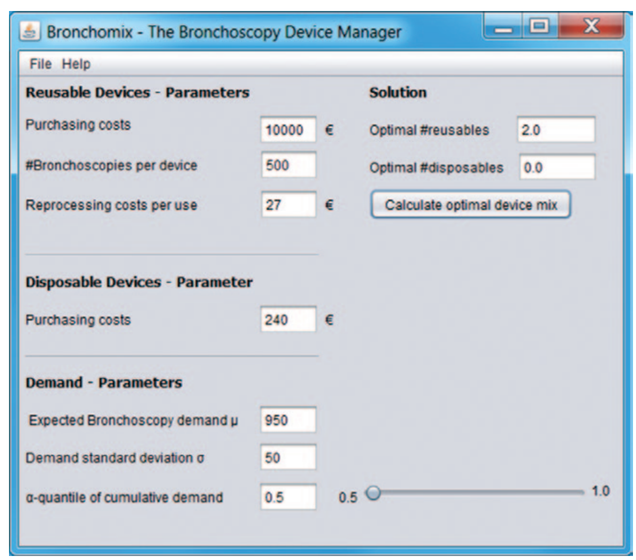

Figure 2. Optimal solution for μ = 950, standard deviation of σ = 50 bronchoscopies, and reliability measure α = 0.5.

Table 1. Cost Parameters for the Economic Analysis

Costs	Reusable Devices	Disposable Devices
Purchase	$10752.50	$258.06
Maintenance and repair/device/year	$3225.75	–
Reprocessing per bronchoscopy	$29.03	–

is that 2 reusable but no disposable devices should be purchased. The example demonstrates that decreasing the reliability measure α leads to a decreasing purchase of devices.

Robustness of Our Results Using Demand Variation

Using a demand factor between 1% and 500%, we multiplied the baseline demand of 950 bronchoscopies. Figure 3

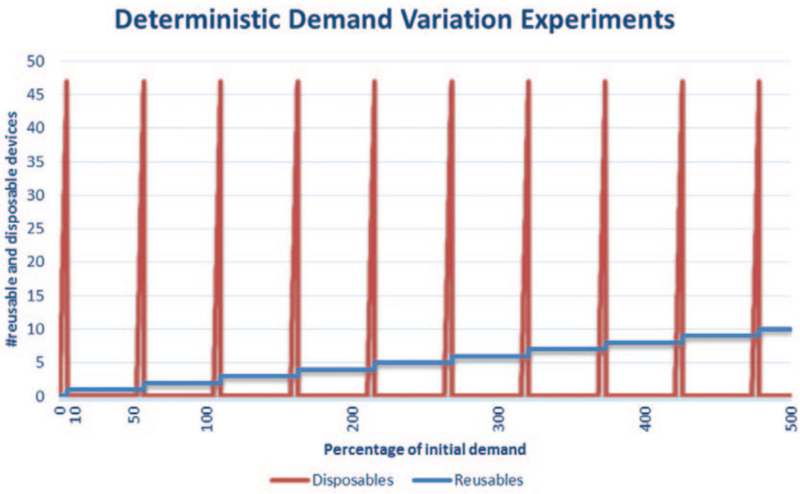

Figure 3. Deterministic demand variation experiments depending on the percentage of initial demand.

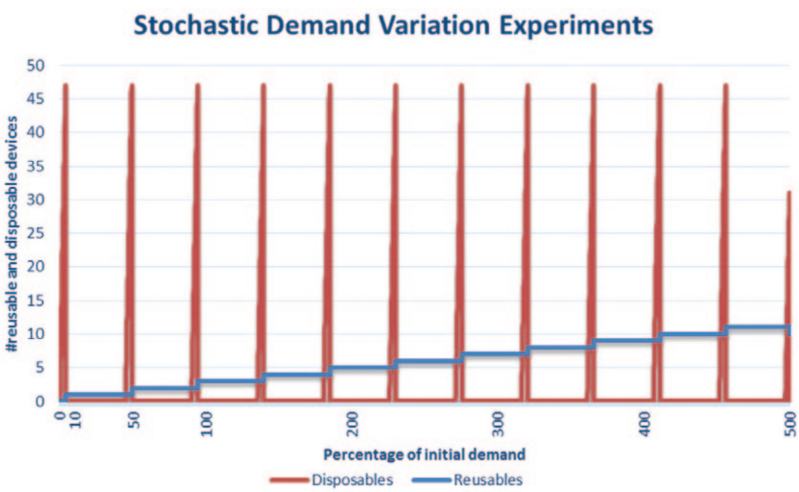

Figure 4. Stochastic demand variation experiments depending on the percentage of initial demand and σ = 10% of expected demand.

shows the demand variation experiments in the deterministic setting where, in the first instance, we ignore variability in demand. The calculations reveal that disposable bronchoscopy devices are efficient in small units, that is, if only 47 bronchoscopies are performed; however, the graph in particular shows that disposable bronchoscopy devices are used to demand ranges in which it is not yet efficient to buy a new device. In these cases, a mix of devices is beneficial and the mathematical model decides to cover capacity shortages with disposable devices. Finally, with a demand factor of 5 times the baseline demand, 10 reusable devices have to be purchased to be economically efficient.

In contrast, Figure 4 shows the demand variation experiments in the stochastic setting. The setting is similar to the one of Figure 3; however, we set $\alpha = 0.95$ and used a $\sigma = 10\%$ standard deviation of the demand. This means that, for example, when the demand factor is 50%, which means that $\mu = 475$ bronchoscopies are expected, then the standard deviation of demand comes up to $\sigma = 47.5$. When we compare both figures, Figure 4 shows more peaks as compared with the ones of Figure 3 that can be explained by the additional number of reusable devices that have to be purchased because of the risk-averse reliability measure paired with the demand variation.

DISCUSSION

In this article, a model and a decision support tool capable of calculating the optimal portfolio of reusable and disposable bronchoscopic devices with regard to costs is developed and presented. Previous studies, for example, in ureterorenoscopy[9] and fiberoptics[2,6,7] have been conducted to investigate similar questions. Because of geographic variations in pricing and reusability cycles, each type of endoscopic device deserves separate evaluation per country and hospital structure. Many of those studies are only applicable to the specific country or even hospital.

In these studies, for example, big variations between costs of an intubation using a disposable bronchoscopic device were observed. McCahon and Whynes[7] report potential savings of up to one-third of total costs by using a single-use device. In the study of Aïssou et al,[8] a cost saving of only 3% is reported, whereas Tvede et al[2] report 15% greater costs when using disposable bronchoscopic devices, which vanish when videoscopes are used. These studies mirror the fact that local prices, repair, and maintenance costs, as well as lifetime cycles of the devices can differ significantly. Another explanation for this high variability is the fact that teaching hospitals, for example, induce greater maintenance and repair costs[6] because of the lack of experience of the physicians using the equipment.

We present a model that is generalizable. Physicians or hospital managers can enter their specific local prices as well as repair and maintenance costs into the model. To our knowledge, so far only studies have been conducted that compare the costs of exclusive use of either reusable or disposable device. Our model is capable of determining the cost-optimized mix of those 2 types of devices depending on the number of the bronchoscopies performed. Our experimental results reveal that, for hospitals performing only a small number of bronchoscopies per year, low demand variability paired with a low reliability measure, it can be advisable to solely employ single-use devices.

With an increasing number of bronchoscopies, increasing demand variability, and reliability measure, however, the mathematical model recommends the decision to buy reusable devices. An interesting observation is shown in Figures 3 and 4. When demand reaches certain intervals, the model decides to use a mix of reusable and disposable devices instead of buying an additional reusable device. Disposable devices can in certain intervals satisfy fractions of the demand.

Our study was performed on a strategic level. Per-day demand for bronchoscopic devices easily can exceed average levels because of unpredictability as well as uncertainty in the need for bronchoscopic intervention. A tool for decision support in the short-term demand could be subject of further research which then should include peak demand during the day as well as sterilization and reprocessing times for the reusable device. Our study was performed under the assumption that disposable and reusable devices perform qualitatively similar to satisfy the requirements of the procedure. Piepho et al[10] showed that disposable devices can facilitate the tracheal intubation in patients and manikins. A further case series proved the capability of the disposable device for tracheal intubation[11]; however, both articles indicate the lower optical quality of disposable devices. In practice, some situations can only be satisfied by a subset of specific devices or some physicians show preferences for specific devices. These issues, however, can be incorporated into our model by introducing subsets of devices and by ensuring that demand is covered by the different device types and physicians, resembling a matching problem.

CONCLUSIONS

The underlying study compares costs and availability of 2 entirely different bronchoscopic device systems. Procurement and reprocessing costs as well as uncertain demand are taken into account. It is shown that the purchase of a mix of disposable and reusable devices can pose a cost-efficient and demand-satisfying solution. Future research will consider the operational decision level allowing for intraday demand variation.

ACKNOWLEDGMENTS

We thank the entire team of the intensive care unit of Klinikum Rechts der Isar as well as Flavius Zima from the TUM School of Management's Technology and Management-Oriented Business Administration program for developing an early version of our model.

We are grateful to the editors' and the reviewers' comments that helped us to substantially improve our manuscript.

DISCLOSURES

Name: Günther M. Edenharter, MD.
Contribution: This author helped conduct the study, analyze the data, and write the manuscript.
Name: Daniel Gartner, MS.
Contribution: This author helped conduct the study, analyze the data, and write the manuscript.
Name: Dominik Pförringer, MD.
Contribution: This author helped conduct the study, analyze the data, and write the manuscript.
This manuscript was handled by: Nancy Borkowski, DBA, CPA, FACHE, FHFMA.

TECHNICAL APPENDIX

The problem of planning the mix of single-use and reusable bronchoscopy devices is approached by using the following mathematical model: Procurement costs of disposable and reusable devices are denoted by p^d and p^r, respectively. We denote $c^{reprocess}$ as costs including sterilization and repair of reusable devices. The total number of bronchoscopies that can be performed with each reusable device is denoted by n^r. We assume that demand is uncertain and follows a normal distribution with expected value μ and standard deviation σ. We denote demand by $D(\mu,\sigma)$. Furthermore, we denote α as a reliability parameter. We introduce integer decision variables $q^{net,r}, u^r, u^d \in \mathbb{N}$ that denote the (net) quantity how often reusable devices are used, and the number of reusable and disposable devices to be purchased, respectively. The decision model reads as

$$\text{Minimize } p^d \cdot u^d + p^r \cdot u^r + q^{net,r} \cdot c^{reprocess} \quad (1)$$

Subject to

$$P(q^{net,r} + u^d \geq D(\mu,\sigma)) \geq \alpha \quad (2)$$

$$n^r \cdot u^r - q^{net,r} \geq 0 \quad (3)$$

$$q^{net,r}, u^r, u^d \in \mathbb{N} \quad (4)$$

Objective function (1) minimizes 3 terms: First, the procurement costs of disposable devices are minimized. In the second term, costs associated with buying reusable bronchoscopes are minimized. Sterilization and repair costs of reusable devices are minimized in the third term of the objective function. Probabilistic constraints (2) ensure that the demand coverage is within the reliability measure α by considering the net number of reusable devices actually in use and the total number of disposable devices. The sum has to be greater than or equal to the demand. To plug in the model into a solver, we reformulated constraints (2) using the deterministic equivalent and used a Java-based lookup function to determine the α-quantile of the normal distribution with parameters μ and σ. Constraints (3) ensure that the quantity that reusable devices can cover is greater than or equal to the net quantity how often reusable devices are actually used. Definitions (4) are the decision variables and their domains.

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