Decision Analysis for Large Capital Purchases: How to Buy a Ventilator

Robert L Chatburn RRT FAARC and Frank P Primiano Jr PhD MBA

We describe a formal decision-making procedure for purchasing intensive care ventilators. We adapted a general decision-making tool known as an additive, compensatory, multiattribute utility model. The model incorporates input from the various stakeholders in the decision. It identifies the factors that are important in the decision and the alternative decision options, weights the factors, ranks the alternative decisions on how well they serve the factors, and finally provides an overall score that identifies the best option. This model provides a more objective and analytical approach than is often used in purchasing decisions. The benefits include simplifying discussion among stakeholders and assisting administrators in justifying major purchase proposals. *Key words: decision analysis, purchasing, ventilators.* [Respir Care 2001;46(10):1038–1053]

> "Most of our daily experience goes before our senses and passes through our feelings like a hazy cloud that slightly moistens the environment but makes little difference to the growth of our understanding."
>
> —Dr Thomas L Saaty

Introduction

The standard accounting approach to making large capital purchases involves the calculation of various financial indices. These may include such items as return on investment, project payback period, and net present value of cash flow, among others.[1] But in hospitals, most department directors (and particularly respiratory care depart-

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Robert L Chatburn RRT FAARC is affiliated with the Respiratory Care Department, University Hospitals of Cleveland, and the Department of Pediatrics, Case Western Reserve University, Cleveland, Ohio. Frank P Primiano Jr PhD MBA is affiliated with Amethyst Research LLC, Philadelphia, Pennsylvania.

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Correspondence: Robert L Chatburn RRT FAARC, Respiratory Care Department, University Hospitals of Cleveland, 11100 Euclid Avenue, Cleveland OH 44106. E-mail: robert.chatburn@uhhs.com.

ment directors) do not have formal business administration training. Therefore, they may not be familiar with the routine tools used to justify project costs. More often, large capital purchases for patient care equipment are based on subjective impressions gained during short trial periods and product in-services provided by the manufacturers. This approach is suitable for many types of equipment in which the features are fairly obvious and the cost is under a few thousand dollars. Mechanical ventilators, however, are different. They are relatively expensive ($10,000 to $30,000) and so complex that only a small fraction of their capabilities can be observed during even a prolonged trial period of actual patient care. This is especially true in the case of a newly introduced machine or one that is new to the department personnel.

When evaluating several complex alternatives, it is helpful to use a systematic approach to decision-making. The process can be fairly complicated if there are many factors to consider that combine in different ways to create various outcomes. For example, in choosing a ventilator we would like to rank several alternative choices on various characteristics (eg, cost and technical features), each with its own arbitrary measurement scale (eg, present value and user satisfaction scores). We would also like to weight the relative contribution of each characteristic to the overall decision (eg, purchase price might be more important than user preference for alarm features).

Herein we present one approach for selecting the best of several alternative actions. We employ a formal structure[2,3] that makes explicit both the factors that are considered important in the decision and how important they are considered to be. This is accomplished by assigning a subjective weight to each factor. The factors can be either objective (eg, cost) or subjective (eg, ease of use), but their relative importance and how the choice measures up to them must all be quantifiable in some way. A simple mathematical analysis is applied that results in a (utility) score for each alternative action. The alternative with the highest score is then the recommended choice. To illustrate the process, we will use the example of purchasing a mechanical ventilator suitable for use in a hospital intensive care unit (ICU). We provide a step-by-step procedure for creating a capital purchase plan, along with a template for comparing ventilator brands. This example is based on an actual capital budget proposal we developed at University Hospitals of Cleveland. We refer to the ventilators as A, B, or C instead of using their real names, because the particular cost data and factor-weighting scheme we used may differ from that used by others, and we do not mean to suggest that the ventilator most appropriate for our situation should be a universal solution.

Justifying the Proposal

Historical Perspective

University Hospitals of Cleveland is a large tertiary care hospital in an academic environment. The respiratory care department serves neonatal, pediatric, and adult ICUs, with an inventory of 92 mechanical ventilators. An examination of this inventory showed that our department had a large proportion of outdated equipment. However, to justify a capital replacement purchase on the order of a million dollars requires more than a suggestion that newer equipment is desirable. Senior management and physicians alike needed to be briefed on the status of the department's current technical capabilities. To do this properly requires some historical perspective. In the case of mechanical ventilators, we found it useful to describe the evolution of technical design in terms of generations. Mechanical ventilators have evolved through at least 5 generations of technical improvements in the last 40 years (Table 1). The list in Table 1, along with actual data from a capital equipment depreciation report and consideration of our departmental objectives justified the purchase of ventilators, as described below.

Current Situation Analysis

The department of respiratory care owns 92 mechanical ventilators, from 10 different manufacturers. Grouped according to primary use, there are 31 adult ventilators, 26 pediatric ventilators, 31 neonatal ventilators, and 4 home care ventilators. All of the neonatal and pediatric ventilators are second and third generation. All but 2 of the neonatal ventilators are more than 12 years old. Of the pediatric ventilators, about half are 6 years old and the rest are over 12 years old. The adult ventilators are third generation. They range from 12 to 16 years old. The depreciable life span of a ventilator is 10 years. The time span between technologic generations is about 8 years.

Challenges

The age of our current inventory makes the availability and dependability of equipment uncertain, makes practicing state-of-the-art mechanical ventilation difficult, and makes some procedures impossible. There are several causes. First, ventilators are failing more frequently, which requires increasing expenditures of time and money for repairs, both in our department and in clinical engineering. Also, because these are life support systems, our liability in the event of failure during use is increasing.

Second, the fact that most of our ventilators are third generation (ie, are specialized for neonatal, pediatric, or

Table 1. The Technical Evolution of Mechanical Ventilators Expressed as Generations

Generation	Characteristics	Examples
1st	Simple electrical or pneumatic control circuits Single mode operation Primitive operator interface Uncalibrated or coarsely calibrated dials, levers, aneroid pressure gauges No alarms	Emerson Iron Lung, Bird Mark series, Emerson Post Op, Baby Bird

2nd	Simple analog electronic or fluidic control circuits
	  On-off flow control
	Restricted mode selection
	  Volume-controlled continuous mandatory ventilation
	  Pressure-controlled intermittent mandatory ventilation
	  Continuous positive airway pressure (CPAP)
	Predominantly analog operator interface
	  Switches, knobs, aneroid pressure gauges
	Basic machine alarms
		Bennett MA-1, Bourns BEAR 1, Ohio 550, Bourns BP-200

3rd	Digital (microprocessor) electronic control circuits
	  Software updates possible
	  Proportional flow control to provide various waveforms
	Expanded mode selection
	  Synchronized intermittent mandatory ventilation
	  Pressure support
	Electronic operator interface
	  Light-emitting diode (LED) numeric and text displays
	  Electronic pressure gauge
	  Multi-purpose push buttons
	Advanced machine alarms, system diagnostic messages, and patient status alarms
		Puritan Bennett 7200, Siemens Servo 900, InfraSonics Infant Star

4th	Computerized operator interface
	  Cathode ray tube and liquid crystal displays
	  Text and graphic displays
	Integrated waveform monitoring and calculated lung mechanics, extensive system diagnostics
		BEAR 5, InfraSonics Adult Star, Dräger Babylog

5th	Advanced control software and hardware
	  More accurate control of pressure, volume, and flow
	  One ventilator for neonatal, pediatric, and adult patients
	"Virtual instrument" operator interface design
	  Easy upgrades through software rather than hardware
		Hamilton Galileo, Dräger Evita 4, Puritan Bennett 840

adult patients) requires us to maintain an expanded inventory. This inflates capital investment and operating costs.

Third, there is an increasing body of evidence that the advanced control (eg, patient synchronization, dual control, automatic weaning, and lung-protective strategies) and monitoring capabilities of the fourth and especially fifth generation ventilators result in better outcomes.[4–6]

Fourth, the advent of inexpensive computing platforms has accelerated the development of new generations of ventilator technology. We need to update now and plan for future updates to keep pace with medical technology. It is no longer acceptable to use the same life support equipment for traditional depreciation periods and beyond.

Finally, because our department has been without staff development support for several years, training and continued competency have become major issues. Using 10 different designs of mechanical ventilator has made it impossible for all staff members (including the clinical engineering department staff) to gain expert experience on all systems. This restricts our ability to move staff among ICUs to accommodate census changes. We need to rely on the education support of vendors to keep our staff properly trained. But in order to assure the level of vendor support needed we must decide to use as few designs as possible and consolidate our purchases under 1 or 2 vendors, which reduces education requirements and leverages our purchasing power to motivate continued vendor participation in staff training.

Opportunities

A number of ventilator manufacturers have merged under large, multinational companies. This allows a high

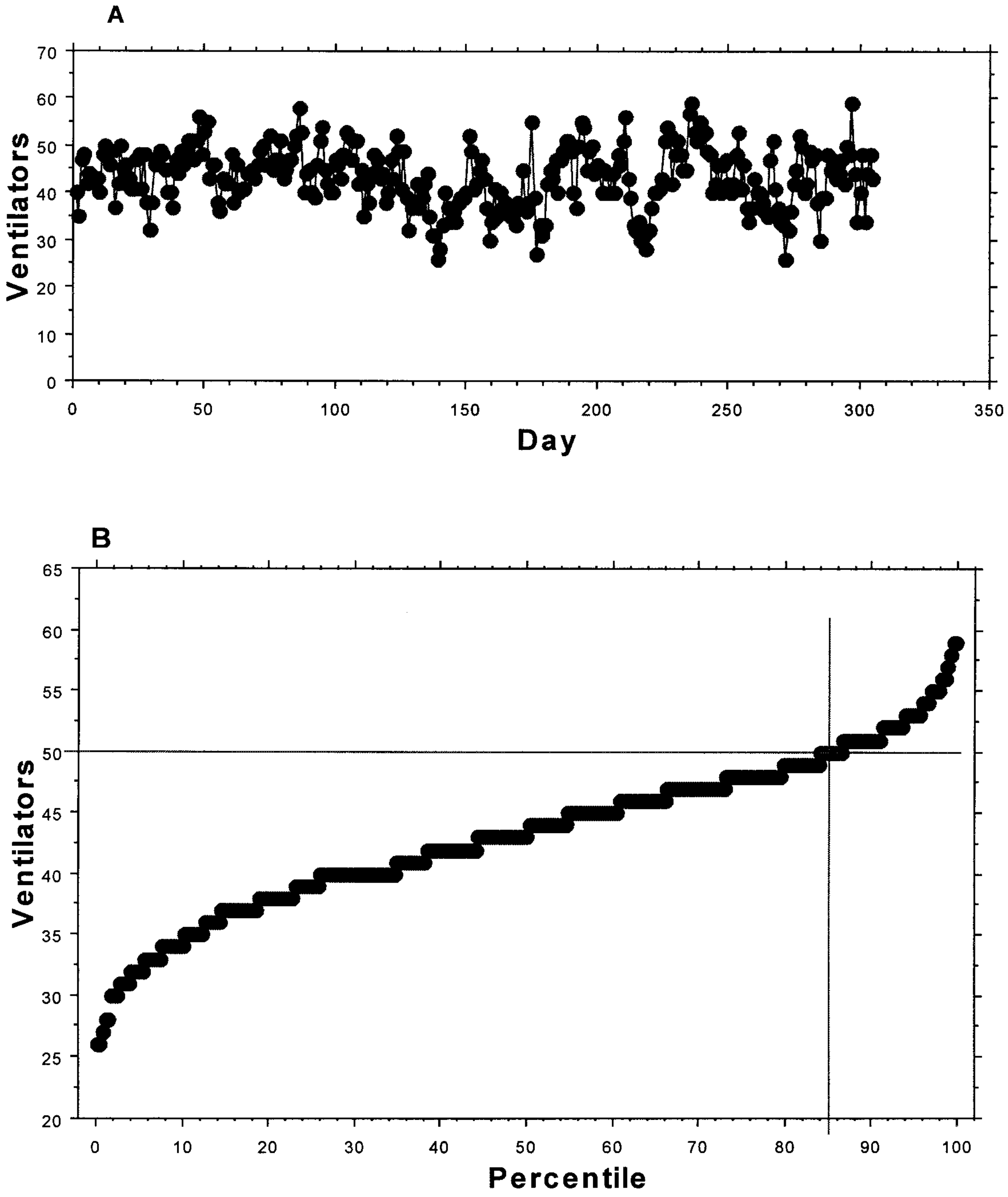


Fig. 1. Estimation of required new ventilator inventory based on graphic analysis of actual ventilator days in 1999. A: Daily ventilator use. B: Percentiles plot showing the percent of time (X axis) that a given number of ventilators (Y axis) were used. For example, the intersection of the thin lines indicates that 85% of the time we used ≤ 50 ventilators per day.

degree of vertical integration, so that any particular company can now provide sales and service for a full range of devices. This range includes neonatal, pediatric, and adult ICU ventilators, as well as home care ventilators. Mergers have also allowed these companies to offer more attractive pricing structures, at least while competitive conglomerates exist, because of the huge financial reserves of larger parent companies.

From a technical standpoint, the current leaders in ventilator manufacturing have developed or acquired ventilators that can function with every type of patient, rather than requiring different models for different populations.

This allows hospitals to carry a smaller inventory of ventilators and reduces maintenance expenses. It also simplifies training and helps to assure a more uniform skill level among more employees.

Some of the new ventilator designs are based on computerized control systems and operator interfaces. These allow upgrading to different versions primarily through software changes rather than hardware modifications, thereby potentially reducing future costs.

In summary, the goals of the purchase of new ventilators are to:

- Advance our patient care capabilities and increase staff competence
- Provide an appropriate technical platform for future updates and upgrades
- Reduce maintenance and rental costs
- Reduce capital inventory

Decision Analysis Procedure

Though all 92 of our current ventilators will need to be replaced in the next 5 years, we decided to begin by replacing just 50. This number of ventilators was selected on the basis of 2 facts:

1. It will replace the oldest ventilators used in the adult and pediatric ICUs.
2. Fifty ventilators will be enough to accommodate our daily patient load 85% of the time (Fig. 1).

Our selection process consisted of 7 phases: (1) application of screening criteria to narrow the number of alternatives, (2) request for proposal (RFP), (3) initial in-service and clinical use of a variety of new ventilators in the ICUs, (4) cost analysis, (5) technical evaluation, (6) data summary, (7) results reporting.

1. Screening

Initial screening criteria were used to limit this analysis to the most appropriate choices. The criteria included the following ventilator characteristics:

- Designed for intensive care use
- Ability to ventilate neonates, children, and adults
- Manufactured by a large, stable company with a good track record of service coverage in our area
- Supported by training materials and personnel supplied by the manufacturer
- Upgradeable primarily by software, without the need for hardware modifications

2. Request for Proposal

Once the vendors and their products were screened, we created an RFP that asked vendors to submit bids and plans to meet our specific needs. In this case we requested vendors to show not only how they could help us achieve our project goals but also to compare an asset management strategy (ie, vendor retains ownership of equipment but provides a just-in-time ventilator inventory and all maintenance needs) with a conventional capital purchase.

An RFP, as a formal, written proposal, helps to ensure that information is equally and fairly shared among all parties. It is useful to organize the RFP into specific sections,[7] including

- Questions regarding the company and product background
- Technical analyses (including comparison with other vendors' products)
- Customer support plans
- Training plans
- Strategies for implementing the changeover to new equipment
- Information management (eg, staff competency data, machine repair, and routine maintenance record keeping)
- Costs for consumables
- Maintenance and repair costs
- Any value-added services
- Purchase/lease prices, payment terms and conditions, delivery dates, warranties/return goods policies, etc

Vendors were invited to submit written responses to our RFP and also to make personal presentations. The presentations were helpful in answering questions and refining our requests.

3. Initial Clinical Evaluation

Demonstration units of current fifth-generation ventilators were provided to our department by the major vendors over the span of about 18 months. The purpose of this phase was to familiarize the staff with the technology and get some experience using the devices with patients. It also gave us a chance to judge the degree of customer support we might expect. Though the staff may have formed some opinions about ventilator performance, these were highly subjective, and the patient outcomes they remember anecdotally cannot be used as a basis for comparison of the ventilators. The availability of computerized ventilator simulations would have greatly decreased the time necessary for this phase by allowing staff to become familiar with the features and operating characteristics of a "virtual ventilator." Such simulations are just now becoming available (see the simulated Newport E100 ventilator at www.ventworld.com).

4. Cost Analysis

The University Hospitals of Cleveland purchasing department analyzed both capital purchase and lease data

Table 2. Financial Analysis Performed by the Hospital's Purchasing Department, Based on Vendor Bids, for the Purchase of 50 Ventilators

Ventilator Model	Cost* Each	Total Cost (with trade-in)	Warranty (y)	Annual Service Cost	Annual Lease Expense	Total 4-Year Cost	
						Own	Lease
A	29,398	1,282,429	3	143,500	1,066,143	1,425,929	4,264,572
B†	20,124	856,200	2.5	111,800	410,094	1,023,900	1,640,376
C	28,782	1,089,118	2	60,258	721,920	1,209,634	2,887,680

*All costs and expenses are in U.S. dollars.
†3rd year limited warranty: parts only

from the manufacturers. Table 2 shows the results. The total 4-year cost to own includes full service maintenance agreements after warranties expire. The cost to own without service contracts is shown in the column titled "Total Cost (with trade-in)." We will trade in 52 of our current ventilators (based on age) for 50 new ventilators. As the new ventilators begin to be used in all areas and as the remaining older ones are retired over the next 3–5 years, we believe the total inventory of ventilators might be reduced by as much as 25% if we acquire equipment with the comprehensive capability to ventilate neonates, children, and adults.

The cost analysis shows that the lease or "asset management" option is much more expensive than capital purchase. Even with all the promised advantages of asset management (eg, continued training support, free upgrades, use tracking/adjustment), it is difficult to justify the greater expense over the life of the ventilator (10-year, straight line depreciation). Even for the least expensive option (Ventilator B) the lease cost would exceed the capital cost in a little over 2 years.

Regarding depreciation, it is clear that ventilators last longer than 10 years. It might seem fiscally prudent to keep a ventilator until its repair costs outweigh its replacement cost. However, our analysis of the evolution of ventilator technology (see Table 1) implies that the older the ventilator fleet is, the more likely it is that clinicians will not be able to provide the standard of care. Not meeting the standard of care could eventually lead to increased liability costs.

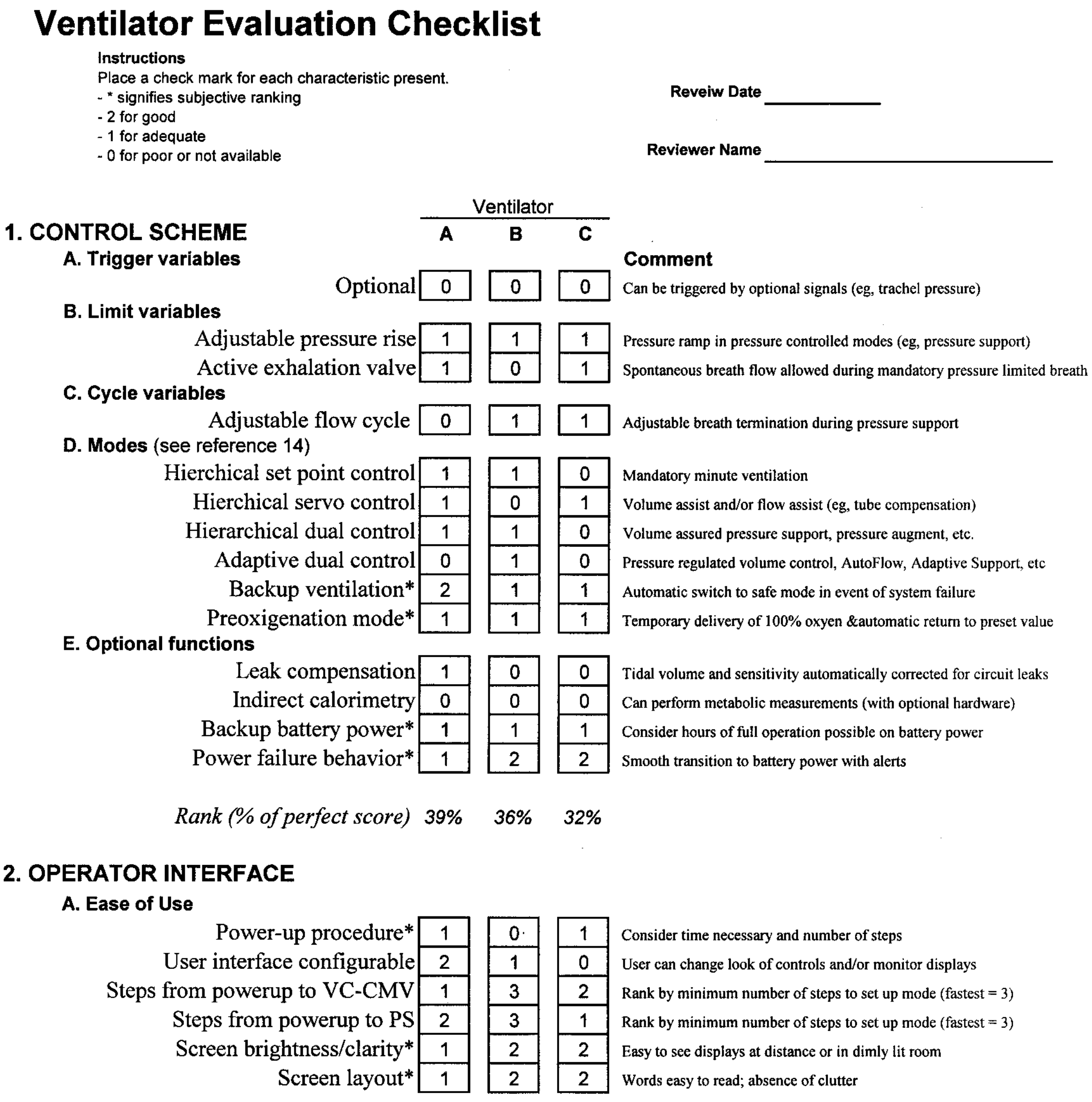
Operating costs are expected to be equivalent for all ventilators because they all use the same disposable patient circuit. Ventilators A and B, however, use flow sensors, the additional costs of which are difficult to estimate because we have no use data. Given our lack of experience with the new ventilators, the maintenance contract costs provide us with the best estimate of expected repair costs.

Note that our analysis of total cost to own was simplified to be just the sum of the expected capital and maintenance costs (after the warranties expired). However, if a more complicated arrangement is considered, whereby various payments are made over an extended period of time, then a true present value analysis should be performed (which would take into consideration inflation and interest data) along with a consideration of opportunity costs.[8,9]

5. Technical Evaluation

The technical evaluation of the candidate products considered previously published guidelines and descriptions.[10–12] Each vendor was requested to give a sales presentation and review his or her product's features. Then each ventilator was connected to a lung simulator and was available for testing for 1 week. A panel of reviewers was selected from the staff (1 physician from each ICU, 2 pediatric and 2 adult respiratory therapists from each shift, the administrative managers, a technician from clinical engineering, and the director of respiratory care). Each ICU was asked to select its own representative, and the supervisors from respiratory care selected the therapists. The clinical engineer who has historically been involved with our ventilator repairs was the natural selection from his department. At institutions in which nursing is very involved with ventilator management, it would be important to consider including them. The director of respiratory care approved the final list of reviewers.

The vendors assisted the reviewers in simulating ventilation scenarios to provide a means for comparing functionality and ease of use without the limitations imposed by actual patient treatment. Reviewers were given a checklist that provided a mechanism for quantifying specific desirable features for the data analysis phase (Figure 2). The checklist was specially prepared to identify key features and was organized in an outline format. The features were both clinically relevant (ie, might affect patient outcome or operator efficiency) and could potentially differentiate one model from another (see Discussion section below for detailed description). For example, waveform monitoring features were included because they affect ventilator management and because the models we examined varied in the types of features offered. On the other hand, the presence of pressure and flow-triggering was not included, because all ventilators had these features. Like-



Ventilator Evaluation Checklist

Instructions
Place a check mark for each characteristic present.
- * signifies subjective ranking
- 2 for good
- 1 for adequate
- 0 for poor or not available

Reveiw Date ____________

Reviewer Name ______________________________

	Ventilator A	Ventilator B	Ventilator C	Comment
1. CONTROL SCHEME				
A. Trigger variables				
Optional	0	0	0	Can be triggered by optional signals (eg, trachel pressure)
B. Limit variables				
Adjustable pressure rise	1	1	1	Pressure ramp in pressure controlled modes (eg, pressure support)
Active exhalation valve	1	0	1	Spontaneous breath flow allowed during mandatory pressure limited breath
C. Cycle variables				
Adjustable flow cycle	0	1	1	Adjustable breath termination during pressure support
D. Modes (see reference 14)				
Hierchical set point control	1	1	0	Mandatory minute ventilation
Hierchical servo control	1	0	1	Volume assist and/or flow assist (eg, tube compensation)
Hierarchical dual control	1	1	0	Volume assured pressure support, pressure augment, etc.
Adaptive dual control	0	1	0	Pressure regulated volume control, AutoFlow, Adaptive Support, etc
Backup ventilation*	2	1	1	Automatic switch to safe mode in event of system failure
Preoxigenation mode*	1	1	1	Temporary delivery of 100% oxyen &automatic return to preset value
E. Optional functions				
Leak compensation	1	0	0	Tidal volume and sensitivity automatically corrected for circuit leaks
Indirect calorimetry	0	0	0	Can perform metabolic measurements (with optional hardware)
Backup battery power*	1	1	1	Consider hours of full operation possible on battery power
Power failure behavior*	1	2	2	Smooth transition to battery power with alerts
Rank (% of perfect score)	*39%*	*36%*	*32%*	
2. OPERATOR INTERFACE				
A. Ease of Use				
Power-up procedure*	1	0	1	Consider time necessary and number of steps
User interface configurable	2	1	0	User can change look of controls and/or monitor displays
Steps from powerup to VC-CMV	1	3	2	Rank by minimum number of steps to set up mode (fastest = 3)
Steps from powerup to PS	2	3	1	Rank by minimum number of steps to set up mode (fastest = 3)
Screen brightness/clarity*	1	2	2	Easy to see displays at distance or in dimly lit room
Screen layout*	1	2	2	Words easy to read; absence of clutter

Fig. 2. Checklist used to evaluate and compare ventilator brands (ie, brands A, B, and C). VC-CMV = volume-controlled continuous mandatory ventilation. PS = pressure support. autoPEEP = intrinsic positive end-expiratory pressure. (Checklist continued on next page.)

wise, the availability of a touch screen was not included, because it is not clear that it is a specific advantage. It is interesting to note that, psychologically, a touch screen (eg, on the Puritan Bennett 840) seems more satisfying than a universal selector knob (eg, on the Hamilton Galileo) because it gives instant gratification when selecting a control. However, a touch screen may involve a greater number of steps to make a given ventilator change if care is not taken to avoid this in the design stage. In general, it seems to us that ventilator interface designs lag behind, say, computer operating system interfaces, in terms of human engineering sophistication.[13,14] Given that life support devices such as ventilators need rapid control access and status assessment during critical situations, it would be interesting to see research comparing the human engineering features of current machines.

Some ventilators have the capability to record and download ventilator settings, alarm events, and the like to an external database such as an electronic medical record. However, it is not clear that such data would improve patient care or caregiver efficiency. Nor do most hospitals have the information systems infrastructure to make collecting such data practical. Therefore, we chose not to include automatic record-keeping as a discriminating ventilator characteristic.

The checklist compared the ventilators in 3 major areas: control scheme, operator interface, and alarms. The checklists submitted by the review panel were summarized (ie,

	Ventilator A	Ventilator B	Ventilator C	
B. Controls				
Convenient placement*	1	1	2	Controls grouped logically and appropriate for mode
Desired controls available*	2	1	1	Control settings available for any desired adjustment (eg, inspiratory hold)
Intuitively obvious*	2	1	2	Unexpected results avoided (eg, minute ventilation changes tidal volume)
C. Waveform monitoring				
Waveform displays*	1	2	1	Consider number of variables displayed and clarity of layout
Graphic scaling*	2	2	1	Vertical and horizontal axes can be changed manually and/or automatically
Cursor	1	1	0	Movable cursor allows displays of digital values from waveform
Pre/post loops	1	1	0	Can superimpose loops to see change with time/treatment
D. Patient monitor				
Leak	1	1	0	Calculation of % leak (ie, inspired - expired volume)
Tracheal pressure waveform	1	0	0	Real or estimated tracheal pressure monitoring
autoPEEP reporting*	2	2	1	Estimation of inadvertent PEEP
Lung mechanics reporting*	2	2	1	Resistance, compliance, time constant, work, etc. (insp./exp. values)
Digital values configurable	1	1	0	Display of monitored values can be changed
Optional data analysis software	1	1	0	Ability to download and analyze monitored values
Trend reporting*	2	1	0	Graphs parameters over time
E. Optional signals				
Oximeter	1	0	0	Can accept input and display values from pulse oximeter
Capnometer	1	0	0	Can accept input and display values from capnometer
Rank (% of perfect score)	*68%*	*64%*	*39%*	
3. ALARMS				
Nuisance reduction scheme*	0	0	1	Specific software incorporated to reduce nuisance alarms
Alarm screen layout*	1	1	1	Words easy to read; absence of clutter
Default settings*	1	2	1	Default settings logically selected or user adjustable
Retains setting from last use	1	1	1	Alarm settings retained after power-down
Remote alarm option	1	1	1	Can attach a remote alarm device to ventilator
Adjustable alarm sounds	1	0	1	Operator can adjust alarm volume and/or pattern
Smart disconnect	1	1	1	Ventilator stops delivering flow when disconnect sensed
Alarm event log*	2	1	1	Alarm events are stored in memory
AutoPEEP alarm	0	1	0	Alarms if autoPEEP occurs
Rank (% of perfect score)	*44%*	*44%*	*44%*	

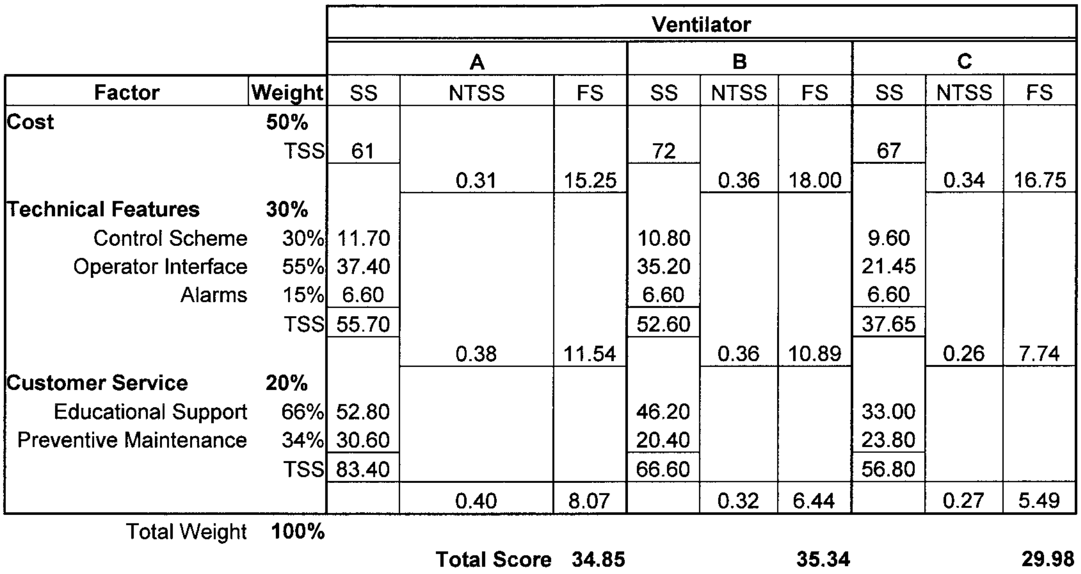
Fig 2. (continued).

average responses calculated) by the technical director of respiratory care. The summarized data were used in the final analysis with the decision-support software (see Fig. 2).

6. Data Analysis

The final selection was made using a Microsoft Excel (Microsoft, Redmond, Washington) spreadsheet based on a procedure described previously[15] and elaborated in more detail herein, in the Appendix. Briefly, several mutually exclusive factors and subfactors in the decision were identified and weighted according to their perceived importance in the final decision. Then the alternative ventilator models were ranked according to the factors. The software then computed a score for each alternative based on the degree that it met the desired factors and the relative importance of the factors (see Appendix). This approach to decision analysis is called an additive, compensatory, multiattribute utility model.[2,3] This model has received the most attention in the literature and has been the most widely applied of all multiattribute utility models. The term "compensatory" refers to the fact that a low value on some attributes can be compensated (or "traded off") for a high value on other attributes. A tradeoff is an expression of how much of one attribute a person would be willing to give up in order to obtain a specified gain in some other attribute.[3]

The ranking grid for this analysis is shown in Table 3, and the spreadsheet layout for the ranking grid is shown in Figure 3. Ventilator rankings on cost and technical features were based on quantitative data (ie, cost analysis and



		Ventilator								
		A			B			C		
Factor	**Weight**	SS	NTSS	FS	SS	NTSS	FS	SS	NTSS	FS
Cost	**50%**									
	TSS	61			72			67		
			0.31	15.25		0.36	18.00		0.34	16.75
Technical Features	**30%**									
Control Scheme	30%	11.70			10.80			9.60		
Operator Interface	55%	37.40			35.20			21.45		
Alarms	15%	6.60			6.60			6.60		
	TSS	55.70			52.60			37.65		
			0.38	11.54		0.36	10.89		0.26	7.74
Customer Service	**20%**									
Educational Support	66%	52.80			46.20			33.00		
Preventive Maintenance	34%	30.60			20.40			23.80		
	TSS	83.40			66.60			56.80		
			0.40	8.07		0.32	6.44		0.27	5.49
Total Weight	**100%**									
			Total Score	**34.85**			**35.34**			**29.98**

Fig. 3. Results grid. SS = subfactor score. TSS = total subfactor score. NTSS = normalized total subfactor score. FS = factor score. See Appendix for explanation of calculations.-

average scores from technical evaluation checklists submitted by review committee members). The technical director of the respiratory care department ranked customer service qualitatively with input from the clinical engineering department. A larger number for a rank meant the ventilator more closely met our needs. The higher ranking for Ventilator A on education support was based on the availability of a greater number and higher quality of training materials on specific aspects of ventilation. The greater ranking on preventive maintenance was based mainly on the availability of factory service (vs third-party repair contracts, which happened to be an advantage in our particular case but might not be in other cases), on the fact that the ventilator used fewer machine parts (presumably offering greater reliability and lower repair cost), and the fact that the ventilator was designed to give easier access to the serviceable areas.

Table 3. Ranking Grid*

Factor	Ventilator		
	A	B	C
Cost†	61	72	67
Technical features			
Control scheme	39	36	32
Operator interface	68	64	39
Alarms	44	44	44
Customer service‡			
Educational support	80	70	50
Preventive maintenance	90	60	70

*Rankings are based on financial analysis (cost), ventilator checklist (technical features), and director's analysis (customer service).

†Ventilators are ranked on total cost to own (see Table 2); cost normalized so high cost = low rank.

Ventilator A rank $= 100 \times \{1 - [1425929/(1425929 + 1023900 + 1209634)]\}$

Ventilator B rank $= 100 \times \{1 - [1023900/(1425929 + 1023900 + 1209634)]\}$

Ventilator C rank $= 100 \times \{1 - [1209634/(1425929 + 1023900 + 1209634)]\}$

‡Ranking scale for customer service: 100 = ideal, 50 = average, 0 = worthless

7. Results

The spreadsheet analysis generated the results matrix shown in Figure 4, the equations for which appear in Table 4. It is important to note that our factor-weighting scheme was designed to support our goals of advancing the standard of care and increasing staff skill level. If the ventilators were evenly ranked on technical features, then the least expensive device would be chosen. However, if price were related to features, then our decision would favor a higher technical level at moderate cost.

Weighting of the factors and subfactors is not straightforward. Improper weighting can negate the entire process. We attempted to assign weights *a priori* by consensus of the evaluation committee. However, our initial low weight on cost (25%) mandated the purchase of the most expensive ventilator that had only a slight technical advantage. When cost was weighted at 50%, the result seemed (to our senior vice president) a more reasonable tradeoff between cost and capability. An alternative approach is to not weight cost but rather to express the final result as a benefit/cost ratio[16] (see Conclusions section below). A more rigorous approach to assigning weights involves generating a matrix of pair-wise comparisons among the factors (using an arbitrary numeric scale where, say, 1 means equality and 9 means that one is extremely better than the

Ranking grid (numeric values)

	Ventilator		
Factor	A	B	C
Cost	61	72	67
Technical Features			
Control Scheme	39	36	32
Operator Interface	68	64	39
Alarms	44	44	44
Customer Service			
Educational Support	80	70	50
Preventive Maintenance	90	60	70

Results grid (numeric values)

		Ventilator								
		A			**B**			**C**		
Factor	**Weight**	SS	NTSS	FS	SS	NTSS	FS	SS	NTSS	FS
Cost	**50%**									
	TSS	61			72			67		
			0.31	15.25		0.36	18.00		0.34	16.75
Technical Features	**30%**									
Control Scheme	30%	11.70			10.80			9.60		
Operator Interface	55%	37.40			35.20			21.45		
Alarms	15%	6.60			6.60			6.60		
	TSS	55.70			52.60			37.65		
			0.38	11.45		0.36	10.81		0.26	7.74
Customer Service	**20%**									
Educational Support	66%	52.80			46.20			33.00		
Preventive Maintenance	34%	30.60			20.40			23.80		
	TSS	83.40			66.60			56.80		
			0.40	8.07		0.32	6.44		0.27	5.49
Total Weight	**100%**									
			Total Score	**34.76**			**35.25**			**29.98**

Ranking grid (cell labels)

	Ventilator		
Factor	A	B	C
Cost	A1	A2	A3
Technical Features			
Control Scheme	A2	B2	C1
Operator Interface	A3	B3	C3
Alarms	A4	B4	C4
Customer Service			
Educational Support	A5	B5	C5
Preventive Maintenance	A6	B6	C6

Results grid (cell labels)

		Ventilator								
		A			**B**			**C**		
Factor	**Weight**	SS	NTSS	FS	SS	NTSS	FS	SS	NTSS	FS
Cost	**WC**									
	TSS	A11			B11			C11		
			A12	A13		B12	B13		C12	C13
Technical Features	**WTF**									
Control Scheme	W2	A21			B21			C21		
Operator Interface	W3	A31			B31			C31		
Alarms	W4	A41			B41			C41		
	TSS	A51			B51			C51		
			A22	A23		B22	B23		C22	C23
Customer Service	**WCS**									
Educational Support	W5	A61			B61			C61		
Preventive Maintenance	W6	A71			B71			C71		
	TSS	A81			B81			C81		
			A32	A33		B32	B33		C23	C33
Total Weight	**WTOT**									
			Total Score	**AT**			**BT**			**CT**

Fig. 4. Spreadsheet layout for decision analysis. Call labeling (letter and number) is arbitrary and does not correspond to normal spreadsheet column and row designations. SS = subfactor score. TSS = total subfactor score. NTSS = normalized total subfactor score. FS = factor score. See Appendix for explanation of calculations.

Table 4. Equations for Spreadsheets Shown in Figure 4

Grid Equation*	Comment
$A11 = A1$	Total subfactor score (TSS) for cost. (For factors with no subfactors, TSS = factor rank × 1.0)
$A21 = W2 \times A2/100$ $A31 = W3 \times A3/100$ $A41 = W4 \times A4/100$	Subfactor score (SS) for technical features: SS = subfactor weight (as a decimal) × subfactor rank
$A51 = A21 + A31 + A41$	Total subfactor score (TSS) for technical features
$A61 = W5 \times A5/100$ $A71 = W6 \times A6/100$	Subfactor score (SS) for customer service
$A81 = A61 + A71/100$	Total subfactor score (TSS) for customer service
$A12 = A11/(A11 + B11 + C11)$ $A22 = A51/(A51 + B51 + C51)$ $A32 = A81/(A81 + B81 + C81)$	NTSS: TSS normalized by the sum of all TSS in row
$A13 = 100 \times WC \times A12$ $A23 = 100 \times WTF \times A22$ $A33 = 100 \times WCS \times A32$	Factor score (FS): factor weight (as a percent) × NTSS
$WTOT = WC + WTF + WCS$	Total of weights (note: also, $W21 + W31 + W41 = W61 + W71 = 100\%$)
$AT = A13 + A23 + A33$	Total score for Alternative A

Equations are shown for Alternative A. Use corresponding equations for other alternatives (ie, substitute alternative letter for A).
*A1 through C6 contain ranking data

other) and then calculating relative weights using eigen vectors.[16–18] The same approach can be applied to ranking the alternatives in the absence of an evaluation tool such as our ventilator checklist.

Purchase Recommendation

Based on this analysis, we recommended the purchase of Ventilator B. We further recommended that installation and implementation be completed within a 6 month period to optimize staff education. It might be more financially convenient to spread the purchase over 18–24 months, but that would severely impair training efforts. Staff would be forced to maintain competence on the many current ventilator brands as well as focus on the new model, making it difficult to get buy-in and commitment. A delayed implementation would negatively affect all of the goals stated in the background section.

Discussion

Managers often make business purchases with the same methods they use in their personal lives. That means their decisions are mainly influenced by the charisma of the sales person and the allure of the presentation, advertising, and packaging, rather than by any systematic analysis of relevant product features. Managers with extensive experience and good instincts seem to be successful with this approach, particularly when the purchase costs are relatively low and the equipment's use is relatively specialized (eg, laboratory equipment). In our case, the cost was huge and we needed to achieve consensus among a large number and wide variety of stakeholders. Furthermore, the stakeholders were accustomed to justifying purchases according to the unique needs of their specialty (ie, pediatric vs adult ICU areas) and at first resented any attempt to "standardize."

The technical analysis of the ventilators was a key component of our proposal. The checklist used to compare ventilator features was organized to match the standard ventilator classification system.[10] As such, it is applicable to any type of ventilator. However, the specific features for a given outline item might vary, depending on the type of patient population being served. For example, if we had wanted to evaluate transport ventilators, we would have had fewer items listed for comparison under modes, and there would be no category of "waveform monitoring" under operator interface. The specific rationales we used were as follows:

1. Control Scheme

a. Trigger variables. Because all ventilators had both pressure and flow-triggering, the only distinguishing feature was the ability to trigger on an optional external signal (eg, tracheal pressure). As it turned out, none of the ventilators we looked at offered this option.

b. Limit variables. All ventilators had pressure, volume, and flow limiting capabilities. What distinguished them was whether the pressure rise to the pressure limit could be adjusted. Also, not all had an "active exhalation valve," which allows spontaneous breaths to occur during a mandatory, pressure-limited breath.

c. Cycle variables. The only discriminating cycle variable was an adjustable breath termination for pressure support.

d. Modes. There has been a definite evolution in ventilator control schemes, which has led to many new modes, with various levels of sophistication. A detailed description of these control schemes and the features of ventilator modes has been presented elsewhere.[19]

e. Optional functions. Leak compensation was a distinguishing factor. All ventilators had battery backup power, but there were differences in how long it would last. One of the ventilators had what we felt were inadequate alerts when the regular alternating current power was removed during operation.

2. Operator Interface

a. Ease of use. Being essentially computers, the ventilators differed in the time it took to boot up. They also differed in the user-configurable display features. It was enlightening to count the number of steps required to go from power-up to a standard mode of ventilation such as volume-controlled continuous mandatory ventilation or pressure support. A step was defined as the movement of the hand from one control (or screen location) to another. If multiple changes could be made without moving the hand from a control, then a step was defined as selection of a parameter along with adjustment of the parameter value (eg, select tidal volume and adjust to 500 mL). Screen clarity and layout appeal were subjective assessments, and there was a fairly wide variation among ventilator brands.

b. Controls. The layout of controls was a subjective evaluation but seemed important to the staff.

c. Waveform monitoring. There was a great deal of variation among the ventilators on this feature. Waveform monitoring should be designed to facilitate bedside evaluation of the condition of the equipment and the patient, including comparison between 2 time periods (eg, pre- and post-bronchodilator flow volume loops).

d. Patient monitor. Because a leak (in the patient circuit, around the endotracheal tube, or through a chest tube) will affect the accuracy of lung mechanics calculations,[20] as well as affect gas exchange, it is important that the leak size be estimated and displayed. Trending of key parameters (particularly resistance and compliance) is important to gauge the effectiveness of lung-protective strategies and other therapeutic maneuvers.

e. Optional signals. Several parameters derived from noninvasively-measurable respiratory variables have gained increasing acceptance as indicators of patient status. Two that are becoming routine additions to ventilator displays (along with their associated waveforms) are arterial oxygen saturation (measured by pulse oximetry) and end-tidal CO_2 (measured by capnometry).

3. Alarms

A nuisance alarm reduction scheme is a sensible feature that was well thought out on one ventilator. Alarm screen layout and the appropriateness of default settings were subjective but important practical evaluations. Another very important feature for the bedside caregiver is the use of what might be called “smart disconnect” software algorithms. This means the ventilator senses that the patient has been disconnected and does not try to ventilate the room with a huge rush of gas and a lot of noise.

Features other than those we focused on exist, but our selection of these was based on our need to evaluate ICU ventilators. A decision-maker must include or eliminate from the checklist those features appropriate to the class of ventilators under consideration. Features unique to a particular member of a class can be included if their consideration would affect the member’s ranking compared to the others.

Conclusions

The analytic approach to decision-making we used was very helpful in the discussion stage, in which panel members came together to achieve consensus. It forced relevant issues to be included in the dialogue and the priorities to be stated, while tending to avoid digressions along unproductive lines of discussion. The data collection form provided a mechanism by which stakeholders could contribute input into the final decision according to their experience. Meetings to brainstorm relevant product characteristics and weightings created a sense of ownership that is necessary to assure success in the implementation phase. Psychologically, the decision model gets stakeholder participation in a nondisruptive manner, leaving the discussion free to focus on each individual’s considered judgment without having to defend the relevance of that judgment.

It was surprising to us that it was relatively easy to get consensus, across all users, on the ventilator that ranked highest on technical features. For example, clinicians in pediatric patient care areas typically view their equipment needs as being distinctly different from clinicians in adult care areas. The few people who dissented were not on the review panel. Their arguments tended to be simply statements of their preferences, without any specific rationale. Without a framework for making decisions, such statements could influence the final outcome in proportion to the perceived authority of the individual. Though that might not be a bad thing, it is certainly not a rational process.

We were not able to reach consensus on cost. The clinical staff felt that cost should be a minor factor, as our main goal was to improve our patient care capabilities. Our administrator was sympathetic with that view but was constrained by the available capital budget. Some felt that weighting cost was simply a way of forcing that factor to dominate the decision, which tended to cast suspicion on the whole process.

One way around this conundrum is to simply take cost out of the initial factor analysis and then account for it later in the form of a benefit/cost ratio.[16] For example, in Figure 4 we could weight cost at 0% (this removes it from consideration as a factor) and increase the weights of the remaining factors proportionally (ie, technical features = 60% and customer service = 40%). This results in final scores of: A = 39.20, B = 34.67, C = 26.13, which are used to quantify the “benefit” of each ventilator. Next, in Table 3, recalculate the cost ranks such that a low number reflects a low cost and a high number reflects a high cost (ie, the cost of each ventilator is simply expressed as a decimal percentage of the sum of the costs of the 3 ventilators). This results in cost ranks of A = 0.3897, B = 0.2798, C = 0.3305. Finally, evaluate the benefit/cost ratios:

- A = 39.20/0.39 = 101
- B = 34.67/0.28 = 123 *(best choice)*
- C = 26.13/0.33 = 79

The final decision has not changed using this method, but the differences among the alternative choices are greater, and it may be more intuitively satisfying. It avoids completely any argument about the relative importance of cost compared to the other factors and casts the final decision in a mathematical form that may be more familiar to health care workers who are used to thinking in terms of benefit/risk.

The formal procedure described here produces documentation that facilitates efficient and confident communication with upper administration. And it serves to record our rationale in the event that we need to review it in the future (eg, for similar additional purchases). Our proposal was just one of many competing for a portion of a limited capital budget. Because of the organized presentation of well-reasoned information inherent in the structured decision analysis, our proposal was judged by senior management more favorably than the usual, unsupported, narrative-style budget request. In fact, after reviewing the proposal, our senior vice president decided to initiate a system-wide analysis of ventilator purchase needs. Therefore, we did not make the purchase we recommended but are now considering a much larger purchase, involving 3 to 4 million dollars over the next 5 years for up to 9 of our system hospitals. We intend to use the same decision support process to achieve consensus among those hospitals that participate in the 5-year plan.

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Appendix

Purchase Decision-Making Analysis

The decision process described in this report employs a simplified decision model that logically translates your experience and intuitive thinking into quantitative measures of relative importance to the decision. The model requires that you identify the numerous factors and subfactors you consider important in deciding among available alternatives. It then reduces the consideration of these factors and subfactors to a formalized procedure that assigns a score to each factor for each alternative. The scores for all the factors are summed for each alternative to obtain the total score for that alternative. The alternative with the highest total score is designated the best choice.

Scores are calculated as the products of weights and ranks. Weights are normalized numerical values used to designate the relative importance of each factor with respect to all the other factors. The subfactors of each factor are also weighted relative to each other. Weights are normalized so that the sum of the weights of all the factors (or subfactors of a factor) add up to 1. Ranks are numerical values used to indicate how well each alternative choice satisfies a factor or subfactor.

The actual calculations of the scores for the alternatives are straightforward and can be set up and executed on a spreadsheet (see Figure 4). The real tasks are to choose the factors and subfactors, and to assign the weights and ranks. The choice of weights, by design, formalizes the decision-maker's biases about the factors that bear on the decision. Consequently, it can be used to steer the decision one way or another if the necessarily subjective process of deciding on the weights is not done as objectively as possible. Ranking the alternative choices with respect to the factors is also not straightforward. It requires a thorough understanding of each of the alternatives and the exercise of reasoned judgement in the interpretation of the opinions of the various stakeholders in the decision.

The Process

The following steps are involved in the formalized decision process:

1. Specify the (mutually exclusive) alternatives among which a choice must be made. This defines the decision to be made. Usually the number of alternatives should be narrowed to no more than 5, based on preliminary considerations before the formalized process is begun.

2. Choose the primary factors (also known as summary factors,* usually a maximum of 5) that influence the decision. A factor can have none, one, or more subfactors that apply to it.

3. Choose the subfactors (also known as detail factors*) if any, that relate to each primary factor. Usually a maximum of 5 subfactors is assigned to any one factor. In the "tree" model used here, there is only one level of subfactors. That is, a subfactor does not have any of its own subfactors below it. Note, however, that the Ventilator Evaluation Checklist we used does have sub-subfactors. For example, Trigger variables, Limit variables, and Cycle variables are sub-subfactors under the subfactor Control Scheme, under the factor Technical Features. We did not weight these sub-subfactors (ie, they were considered of equal importance).

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*Chatburn RL. Systematic decision making. Midnight Engineering, Nov-Dec, 1990:68-76.

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Appendix
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4. Choose the weight for each factor relative to the other factors. These weights must total 100% (eg, cells WC + WTF + WCS = 100% in Figure 4, results grid, cell labels). A zero weight for a factor means that the influence of that factor is eliminated from the decision.

5. For each factor, choose the weight for each of its subfactors relative to its other subfactors (eg, cells W2, W3, and W4 in Figure 4, results grid, cell labels). The weights for each group of subfactors must total 100%, and a zero weight for a subfactor means that the influence of that subfactor is eliminated from the decision.

6. Rank each of the alternatives chosen in step 1 (eg, on a scale of 0 to 100, but any scale could be chosen) relative to its ability to satisfy each subfactor (see ranking grid in Table 3, repeated in Figure 4).

   a. When assigning ranks for cost factors and subfactors, the present value of all payments to be made throughout the life of the alternative should be used. This can be obtained from your financial department or computed using payment information and the formula:[†]

   $$PV = \sum_{n=0}^{N} \frac{PMT_n}{(1+i)^n}$$

   in which PV is the present value of a series of payments, PMT_n is the payment made at n years from now ($n = 0$ is the present year), and i is the interest rate.

   b. Usually a higher cost is less desirable than a lower cost and should deserve a lower rank. This means that we would not want to rank the alternatives according to their costs but, instead, would like to rank them in reverse order to their costs. One way to do this is, for each cost factor or subfactor, to divide the cost associated with each alternative by the sum of the costs for all alternatives. Then subtract this fraction from 1 and use the result as the rank. Consequently, the alternative with the highest cost fraction will have the smallest difference from 1 and, thus, the lowest rank, and so on (eg, cells A1, A2, and A3 in Figure 4).

   c. On the Ventilator Evaluation Checklist, we ranked each ventilator on the subfactors based on the percentage of perfect score. For example, the Control Scheme subfactor had 14 sub-subfactors, each of which could get a maximum score of 2. A perfect score on Control Scheme would be 2 x 14 = 28. Thus, the rank for a ventilator as a percentage of a perfect score was the ventilator's cumulative sub-subfactor score divided by 28.

7. Calculate the subfactor score (SS) for each subfactor by multiplying the subfactor's rank (eg, cells A3, B3, and C3 in Figure 4) by its weight (eg, W3 in Figure 4; thus, A31 = W3 × A3).

8. For each factor, add the subfactor scores for each alternative to get the total subfactor score (TSS) for that alternative (eg, cells A51 = A21 + A31 + A41).

[†] Barnett RA, Ziegler MR. Finite mathematics for management, life, and social sciences. 4th edition. San Francisco: Dellen Publishing, 1987:304-307.

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Appendix
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9. Add the TSS for each factor across the alternatives to get the sum of TSS for that factor (eg, A51 + B51 + C51 in Figure 4). For each factor, obtain the normalized TSS (NTSS) for each alternative by dividing that TSS by its associated sum of TSS (eg, A22 = A51/[A51 + B51 + C51] in Figure 4). This step is important to prevent some factors from having inappropriate influence on outcomes because of differences in their ranking scales. For example, the cost subfactor score turns out to be a small number (ie, a fraction) compared to the subfactor scores for technical features and customer service. This happens simply because of the way the rankings are scaled (cost 0–1, technical features 0–infinity, customer service 0–10). If the cost subfactor had not been normalized, its contribution to the total score for each ventilator would have been insignificantly small compared to that of the technical features and would not have reflected the desired 50% weighting.
10. Multiply the NTSS total by the weight of its corresponding primary factor to obtain the factor score (FS) for each alternative (eg, A23 = WTF × A22 in Figure 4).
11. Add the factor scores for each alternative to obtain the total score for that alternative (eg, AT = A13 + A23 + A33 in Figure 4). The alternative with the highest total score is designated the best choice.

A summary of the equations for all the cells in Figure 4 is given in Table 4. If the calculations are set up on a computerized spreadsheet, then it is straightforward to change the weights and ranks to test "what if" scenarios to see the effects of these changes on the decision. Different factors and subfactors can even be added or removed from consideration to evaluate their influences.

An Available Implementation

Constructing a spreadsheet for the decision calculations can be time-consuming and may be impossible if you do not have access to a spreadsheet program. A convenient alternative exists. A purchasing decision tool computer program, which contains a set of default factors and subfactors judged by us to be important in the purchase of mechanical ventilators, is available for purchase from Amethyst Research LLC at its Web site, Ventworld.com.