Medical Technology Investment Decision-Making at Hospitals:

Current Practices and a SMARTer Approach

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Abstract
Investments in expensive medical technologies, ranging from computed tomography (CT) scanners to proton beam accelerators, consume a major share of hospitals’ capital budgets. The demand by physicians, patients and other stakeholders for medical technologies often exceeds a hospital’s financial resources. When allocating their tight budgets, hospitals also need to account for and balance multiple organizational objectives (e.g., financials, quality, access to care). Given these challenges and the importance of the decision, one would expect that hospitals rely on systematic and structured decision processes. The literature on current industry practices is sparse. We therefore elicited pertinent information via semi-structured interviews from administrators at four hospitals. Our findings suggest that a systematic decision process that considers all organizational objectives, analyzes and integrates comprehensive data, and is objective and consistent is rarely applied. Motivated by the opportunity to improve hospitals’ capital investment decision processes and the lack of literature in this domain, we applied and adapted the Simple Multi-Attribute Rating Technique (SMART) to this decision challenge. We conducted a SMART exercise with hospital executives as a proof-of-concept and evaluated its effectiveness and suitability. SMART was well received by the executives, who rated the method as objective, easy to understand, and providing decision clarity.

Keywords: Multiple objective decision analysis, SMART, healthcare, medical technology, resource allocation
1. Introduction

Medical technologies play a critical role in the United States (U.S.) healthcare system, not only because they are essential for effective patient care, but also because they account for a major share of its high and ever rising costs. Healthcare spending in the U.S. has been growing at an average rate of 8.2% per year over the past 35 years, compared to just 6.0% Gross Domestic Product (GDP) growth, and has reached $2.9 trillion or 17.4% of GDP in 2013 (CMS 2014). Medical technologies have been the main driver of the rapid increase in healthcare costs; estimates attribute 50-76% of the growth in healthcare costs to medical technologies (Kaiser Family Foundation 2007, Newhouse 1992). Since hospitals are the main purchasers and users of these technologies, their adoption behavior affects system-wide healthcare costs.

Medical technology adoption (i.e., investment and use) also plays an important role in the financial and clinical performance of a hospital. Physicians rely on technology for diagnosis and treatment, and patients expect and demand the latest and most advanced medical equipment. Medical technologies have become a competitive differentiator for hospitals that compete not only for patients, but also for physicians (employed by hospital, or self-employed affiliates). The problem is that these technologies, even relatively common ones like CT scanners or surgical robots, are expensive to buy, while financial resources are limited at most hospitals (Dreyfuss and Roberts 2011).

In deciding which equipment to buy given a limited budget, hospital executives should prioritize acquisitions by considering their organization’s objectives. Studies have documented that financial performance is the most common decision criterion (Greenberg and Peterburg 2005, Greenberg et al. 2003, Kamath and Oberst 1992, Mukherjee et al. 2015), while quality of care is the most important one for many hospitals (Weingart 1993). Other decision criteria include
strategic aspects (e.g., market share), the needs of different stakeholders (e.g., physicians’
equipment preferences, access to care for patients), and the impact on research and teaching,
among others (Greenberg et al. 2003, Herndon et al. 2007). Factors that further complicate the
medical technology investment decision, particularly for new equipment, are uncertainty or lack
of data on insurance coverage and reimbursements, patient demand, competition, and
technological advancements (Coye and Kell 2006, Wernz et al. 2014). Obtaining reliable data,
accounting for uncertainties, quantifying how an investment would perform with respect to
organizational objectives, resolving trade-offs between these objectives and meeting the needs of
various stakeholders is challenging.

Given these challenges and the importance of the decision, one would expect that hospital
executives rely on a structured and systematic process that supports their investment decision-
making. The academic literature on this topic is sparse, but the little information available is
consistent with the insights we gained during interviews with hospital administrators: the
investment process at most hospitals is ad-hoc, unsystematic, not sufficiently data driven, and
often dominated by politics and favoritism (Atwood et al. 2015, Kleinmuntz and Kleinmuntz
1999, Reiter and Song 2012, Wernz et al. 2014). Healthcare organizations are lagging behind
organizations in other industries, which are more likely to use rigorous and quantitative
approaches for capital investment decisions (Davenport and Harris 2007, Kamath and Elmer

In their defense, standard investment decision criteria, such as net present value (NPV) or
return on investment (ROI), are not sufficient for capital investment decisions at hospitals; other,
non-financial aspects are equally important. Operations research models that account for the
multi-objective nature of the problem (e.g., Focke and Stummer (2003)) are often too complex,
incomprehensible to practitioners, and require unavailable data inputs. As a result, they are rarely used in practice. Hospital executives need an approach that is multi-objective, comprehensive, transparent, and simple to apply (Johnson-Masotti and Eva 2006).

The Simple Multi-Attribute Rating Technique (SMART) (Edwards 1977, Kirkwood 1997) satisfies all of the characteristics mentioned above. SMART has the potential to support hospital executives in carrying out a structured, transparent, objective and consistent decision-making process. SMART accounts for multiple objectives and enables decision makers to combine quantitative and qualitative performance data. SMART is simple, while providing the necessary insights to executives.

We conducted three proof-of-concept exercises to test SMART. The first two exercises were performed with graduate student participants playing the role of hospital executives. The third exercise was carried out with executives at Barnabas Health, the largest integrated healthcare delivery system in New Jersey. Barnabas Health operates six acute care hospitals, two children’s hospitals and numerous other medical facilities (Barnabas Health 2015). The Barnabas Health participants were system-level executives, i.e., they manage and oversee all hospitals and facilities. Their investment approval is required for major capital investments (> $75,000).

In all three exercises, participants were tasked with selecting among medical technology investment alternatives given a limited budget. We held the two student mock exercises to test and select among various SMART implementation variations, and to prepare the moderator for the exercise with the executives. The SMART variations we tested in the student mock exercises were value function assessment and weighting of objectives.

To the best of our knowledge, this is the first paper to provide a detailed description and evaluation of SMART for capital investment decisions in healthcare organizations. It further
provides a comprehensive list of organizational objectives and attributes (see Table 1) that practitioners can draw from when developing a SMART process for their organization. Lastly, the paper addresses a void in the literature on medical technology investment decision-making by discussing insights from interviews we conducted with hospital administrators.

The objectives of this paper are two-fold: (1) to analyze current practices in medical technology investment decision-making at hospitals, and (2) to evaluate the suitability and effectiveness of SMART for this decision problem along with implementation guidelines for practitioners seeking to improve hospitals’ capital investment decision process.

The remainder of this paper is organized as follows. Section 2 describes the current status of the decision-making practice, as reported in literature and based on our interview findings. In Section 3, we describe our SMART implementation, followed by a discussion of the results and suggestions for future directions. Section 4 provides the conclusions.

2. Capital investment decision-making practices

2.1. Findings from the literature

Investment decisions at many hospitals have been described as ad hoc, informal, political and not sufficiently data driven (Atwood et al. 2015, Geisler and Heller 2012, Greenberg and Peterburg 2005, Kleinmuntz and Kleinmuntz 1999, Smith and Wynne 2005, Weingart 1993) and, in general, not sufficiently cognizant of the hospital’s mission and strategy (Coye and Kell 2006, Wernz et al. 2014). Healthcare organizations rarely use rigorous and quantitative approaches for capital investment decisions, and are thereby lagging behind organizations in other industries (Davenport and Harris 2007, Kamath and Elmer 1989, Kusserow 1992).
Medical technology investment decisions are typically driven by physicians’ needs and requests to which hospitals administrators react (Mukherjee et al. 2015). When submitting requests, physicians are often tasked with providing clinical and business relevant information to justify the investment. Supplemental information may be provided by the vendor of the equipment, or is in some instances the main source of information (Atwood et al. 2015). Taken together, administrators often find themselves having insufficient or biased data for their resource allocation decision (Coye and Kell 2006, Sorenson and Kanavos 2011). Physicians have to take on the role of advocates for their purchase requests, which undermines administrators ability for an objective and system-oriented capital allocation (Atwood et al. 2015).

The use of financial performance criteria, such as return on investment (ROI), to inform medical technologies investment decisions is discussed and advocated for in a variety of papers (Atwood et al. 2015, Blanchfield et al. 2005, Kamath and Elmer 1989, Mukherjee et al. 2015, Williams and Rakich 1973). However, a survey conducted in 2004 among 417 hospitals revealed that only 2 to 12% of hospitals used financial tools to assess medical technology investments (Blanchfield et al. 2005). One explanation for the surprisingly low use of financial tools may be that ROI and other financial performance criteria are often difficult to quantify in healthcare settings (Atwood et al. 2015), or are dominated by other considerations (e.g., patient safety) (National Academy of Medicine 2015).

The need for better decision-making tools that can help hospitals select among medical technology investment alternatives while accounting for strategic goals and organizational objectives has been discussed in literature (Focke and Stummer 2003, Johnson-Masotti and Eva 2006). In particular, multi-criteria decision analysis approaches have been identified as ways to
support decision makers in establishing a structured decision process (Linkov et al. 2006, Renkema and Berghout 1997, Roy 2005).

A comprehensive list of objectives that hospitals use has not yet been published, but several surveys with hospital executives describe the most significant factors that influence medical technology investment decisions (David and Jahnke 2004, Greenberg and Peterburg 2005, Greenberg et al. 2003, Kamath and Oberst 1992, Kamath and Elmer 1989, Mukherjee et al. 2015). We collected these factors and grouped them into five categories: Financials, Quality, Strategic Importance, Infrastructure/Capacity/Access, and Ease of Implementation. For each of these five groups, we identified and collected corresponding attributes from a broad spectrum of publications. Table 1 shows our findings.

Insert Table 1 around here

Among organizational goals, financial performance is the most common decision criterion (Greenberg et al. 2005, Greenberg et al. 2003, Kamath and Oberst 1992, Mukherjee et al. 2015), while quality of care is considered the most important in some hospitals (Weingart 1995). Other decision criteria discussed include strategic aspects (e.g., market share), the impact on research and teaching, and the needs of different stakeholders (e.g., physicians and patients) (Greenberg et al. 2003, Greer 1985, Herndon et al. 2007, Teplensky et al. 1995). Many internal and external stakeholders participate in medical technology decisions, which are carried out in multiple stages and represent a compromise between clinicians and administrators (Geisler and Heller 2012). When evaluating new equipment, decision makers face uncertainty or lack of data on insurance coverage and reimbursements, patient demand, competition, life cycle, and
technological advancements, which further complicate the decision (Atwood et al. 2015, Coye and Kell 2006, Wernz et al. 2014).

Insights from the literature are limited to those described above. Literature describing current medical technology decision-making practices is sparse. Most sources only provide recommendations, but do not describe or analyze the way in which decision makers allocate budgets or decide on investments. We therefore collected primary data through semi-structured interviews with hospital administrators.

2.2. Findings from our interviews

We interviewed administrators from four different hospitals across the United States. Our objectives was to obtain first-hand information about hospitals’ medical technology investment decision-making process, the systems they use to support this process (e.g., software), and the challenges they face. These insights contribute to filling a gap in the academic literature, and provide the basis for our ensuring SMART proof-of-concept exercise.

2.2.1. LewisGale Hospital. Montgomery County, VA

The LewisGale Hospital - Montgomery is part of the Hospital Corporation of America (HCA), which employs approximately 204,000 people and comprises 165 locally managed hospitals and 115 freestanding surgery centers in 20 U.S. states and England (Hospital Corporation of America 2015). HCA is divided in three main groups, each with multiple divisions. The LewisGale Hospital - Montgomery is part of the HCA Capital Division. The Capital Division—headquartered in Richmond, VA—includes thirteen hospitals and 30 outpatient centers, employing 15,194 people. In 2014, the Capital Division served more than one million patients, which included 463,886 emergency visits (HCA Virginia Health System 2015). HCA executives across groups and divisions are responsible for different aspects of the medical technology
decision-making process. The interview was held with the LewisGale Hospital CFO in March 2012.

New technology investments are made using various assessment criteria, but not necessarily in a systematic or consistent fashion. The most important evaluation criterion is the hospital’s immediate needs, e.g., equipment that requires replacement due to malfunction, age, or unavailability of spare parts. Competitive advantage and market share are the second most important criteria; if other hospital systems are utilizing new technologies, this can have a direct impact on LewisGale’s market share and competitive positioning in the region. Physicians’ requests and customer demand for new technologies are also evaluated. Decision makers estimate the new equipment’s ROI and payback period, and apply a rule of thumb to determine whether or not the technology will be purchased. If a given technology has a payback period of three years or less, then it will likely be purchased. However, if the ROI and payback period do not support the investment decision, additional factors such as reimbursement from Medicare and commercial payers are considered.

Once hospital executives make the decision to purchase a new piece of medical technology, the ensuing process depends on the investment amount. If the cost of the new technology is greater than $500,000, the purchase is evaluated during a strategic planning process where HCA corporate executives make the final funding decision. The hospital uses the Capital Asset Management System (CAMS) to present the investment case to HCA corporate decision makers. This off-the-shelf portfolio management software helps executives to determine the revenue that will be generated from the investment under evaluation.

If the cost of the new technology is less than $500,000, the hospital can make the decision to invest using its routine capital budget. However, if the hospital is unable to self-fund
the technology, the purchase request can be escalated to division or group level executives, who have the ability and resources to allocate discretionary funds.

2.2.2. Carilion Clinic. Roanoke, VA

Carilion Clinic is a not-for-profit healthcare organization with a network of hospitals, outpatient specialty centers, and primary care practices. Carilion Clinic currently consists of nine hospitals located in the state of Virginia, employing 650 physicians and a total of 11,700 people. In 2014, Carilion Clinic had 877,000 primary care visits, 48,659 admissions and 168,964 emergency department visits (Carilion Clinic 2015). We interviewed the Director of the Center of Innovation at Carilion Clinic in February 2012.

Given the overall smaller corporate size of Carilion, the necessary funding for new technology investments is not as readily available as in HCA LewisGale Hospital’s case. A further difference is that financial aspects such as ROI are not considered as important compared to clinical needs of patients. Although the focus of Carilion Clinic is not on profit generation, the overall investment decision-making process is similar to the one at LewisGale. Medical technology investments are made using a tiered system that represents Carilion Clinic’s priorities:

Tier 1: Replacement of equipment that does not meet regulatory standards.

Tier 2: Replacement of equipment considered unsafe.

Tier 3: Replacement or repair of malfunctioning or non-operational equipment.

Tier 4: Replacement of equipment with few life years left, an expired warranty, or no replacement parts available.

Tier 5: Investments in new technologies.

Medical technology investment requests are initiated by different functions within the hospital (e.g., cardiac group). Requests are evaluated on a first-come, first-serve basis, where
each investment request is assessed on its own merit and is constantly re-evaluated based on newly submitted requests. In contrast to LewisGale, Carilion Clinic hospital executives do not have the opportunity to rely on upper organizational levels to receive additional investment funding and have to allocate a strictly limited budget.

For low-cost medical technologies, committees within the hospital are in charge of making investment decisions. In the case of larger investments, these committees perform an initial review and then pass it on to the financial board for evaluation and the final investment decision. This process is supported by the StrataJazz® software suite.

2.2.3. Wake Forest University Baptist Medical Center. Winston Salem, NC

Wake Forest Baptist Medical Center (WF) is a non-profit teaching hospital funded by the state of North Carolina, the federal government, and private and public insurance companies. 12,563 people are employed at WF hospital and medical school, including 659 physicians. In 2014, WF had 36,363 inpatient admissions, 103,754 emergency department visits, 991,718 outpatient visits, and around 90,000 visits at other locations part of the system (Wake Forest Baptist Medical Center 2015). We interviewed administrators from the finance and operations excellence departments in October 2011.

Investments are divided into three categories: major projects, information technology (IT) investments, and routine replacements. WF has decentralized their decision process, giving departments the ability to decide on the implementation of minor projects independently. Investment decision-making follows a capital budgeting calendar and a predetermined workflow, so that investment requests are completed within approximately three months. Users submit budget requests between the end of March and mid-April of every year. After an initial review, these requests undergo financial planning and administrative reviews. Thereafter, either the Vice
President or the Dean determine when the project is ready for evaluation and prioritization. The prioritization process is supported by the StrataJazz® software suite.

To increase the objectivity of the decision-making process and reduce the influence of hospital politics, WF employs a weighted score that comprises six evaluation criteria to evaluate different medical technology investment alternatives: financial (25%), quality (20%), capacity/access (15%), strategic importance (25%), infrastructure (10%), and ease of implementation (5%). These weights had been determined by a senior leadership group of physicians and operational personnel.

Each project is given a score between 1 and 5 for each criterion. The scores are then multiplied by the corresponding weights. The quality score is determined based on an executive summary of the project's impact on quality, written by the person submitting the capital request. This report might include biased or inconsistent information. NPV and ROI are used as financial criteria; however, there is no clearly defined threshold that any given project has to reach in order to be implemented. A lower scoring project can be preferred if its costs are significantly lower than those of a higher scoring one.

Medical technology investments below $500,000 are prioritized by the department placing the request, while larger investments require a strategic write-up, and are assessed by an enterprise resource strategy group. Funding approvals are usually made by mid-June of every year, and are followed by final price adjustments. Each capital request is tracked to control its actual development. Although the use of StrataJazz® and decentralization efforts are generally regarded positively at WF, financial analysts expressed the need for improved evaluation techniques.
2.2.4. Barnabas Health Medical System. West Orange, NJ

The Barnabas Health medical system includes 10 hospitals, 26 outpatient centers, and 19 specialty centers in the state of New Jersey. It treats over 2 million patients per year, including 1.5 million outpatients, 220,000 inpatients, and 540,000 emergency department patients. It employs over 25,000 people, including 5,200 physicians (Barnabas Health 2015). We interviewed system-level and hospital-level executives in February 2014.

Physicians typically initiate equipment requests, and system-level executives decide on capital investments with costs larger than $75,000. Our interviewees affirmed that capital investment evaluations are not sufficiently data-driven, and are usually performed subjectively. Their process is unstructured, and can vary depending on the purchase cost, the type of technology requested, and the person placing the request. Replacements of critical equipment are prioritized over other investments. Once the necessary funds have been allocated to these replacements, executives decide how to allocate the remaining budget based on new business opportunities or expansion requirements.

Market share is an important evaluation criterion for Barnabas Health executives because of fierce competition with other hospitals in the region. Medical technologies have become significant differentiators in the healthcare sector, and can determine a hospital’s market share and growth. The trade-offs between growth opportunities and equipment replacement requirements add to the complexity of the investment decision-making.

As Carilion Clinic and the Wake Forest Hospital, Barnabas Health also uses the enterprise software suite StrataJazz®. Hospital personnel, in particular physicians, use the StrataJazz® capital planning module to submit their medical equipment requests. Executives review this information during request review. This capital planning module, however, is
primarily used to track previous purchases and monitor the progress of ongoing projects. Executives do not assess purchase requests using the built-in evaluation criteria in StrataJazz® or systematically established criteria associated with their organizational objectives. Rather, investment decisions are in many cases made on an ad-hoc basis, and executives have to rely on their individual judgment and past experience. Moreover, hospital executives do not perform retrospective analyses of medical technology investments to evaluate their previous decisions (i.e., no organizational learning occurs).

With information about the performance of past investments not being available, physicians and others who initiate equipment requests are also negatively affected. They are asked to provide detailed life cycle information about the requested equipment when entering their request into StrataJazz® (e.g., life expectancy, patient demand, and operating and maintenance costs). In the absence of readily available data and the effort it would take to obtain reliable estimates, they oftentimes do not enter the data. At decision time, Barnabas Health executives then find themselves not having sufficient information and the chance of granting the purchase request is reduced significantly.

2.3. Summary of interview findings

All four hospitals we interviewed had established criteria for making investment decisions, though significant improvement opportunities exist. Barnabas Health and Wake Forest Hospital used weights to quantify the importance of different evaluation criteria. However, the weights were chosen without sufficient rigor or input from the organizations’ highest levels (e.g., CEO, board of directors).

While multiple investment criteria were considered at all interviewed organizations, decision makers either do not take all relevant criteria into account simultaneously, or only
consider a subset of these criteria. At Carilion Clinic, investment alternatives are evaluated by considering one criterion at a time instead of a simultaneous consideration that allows for trade-off evaluation. At LewisGale Hospital, decision-making is dominated by financial metrics, such as ROI and payback period, and executives consider non-financial metrics only for certain investments after evaluating their financial performance (i.e., executives consider only a subset of all relevant criteria). Decision makers thus cannot analyze trade-offs directly, might overlook them when comparing medical technologies, and purchase those that seem more attractive only under the evaluation criterion considered first.

All interviewees stated that lack of funds represents a challenge in medical technology investments. Scarcity of resources makes an investment decision that systematically evaluates trade-offs between conflicting objectives (e.g., market share growth vs. immediate infrastructure needs) even more necessary and valuable. Instead, executives’ arguments and motives to support one investment over another are influenced by organizational politics and pressures exerted by equipment-requesting physicians. Politics and favoritism are common at hospitals and result in suboptimal decisions (Mukherjee et al. 2015, Reiter and Song 2012, Smith and Wynne 2005).

Carilion Clinic, the Wake Forest Hospital and Barnabas Health use the StrataJazz® enterprise software to support capital investment decisions. StrataJazz® is a popular software suite used by 20% of U.S. hospitals, and includes cost accounting, budgeting, forecasting and planning functions (Strata Decision Technology 2015). StrataJazz® has a capital planning module that builds upon SMART principles (Kleinmuntz 2007). However, even the company does not know how many hospitals use this module as intended and to its fullest capabilities. StrataJazz® does not guide decision makers through the capital investment evaluation process, nor does it provide them with recommendations on how to conduct this assessment. Barnabas
Health, for example, has an installation of the capital planning module and uses it to record and track capital requests, but not to support capital investment and decision prioritization.

3. Proof of Concept: Multi-criteria Decision Analysis (MCDA) and SMART

SMART is a value measurement model that belongs to the field of multi-criteria decision analysis (MCDA). MCDA has been proposed as a transparent and systematic approach for rational and balanced priority setting. It can analyze trade-offs between various criteria by establishing their relative importance, resulting in a rank ordering of investment alternatives (Baltussen and Niessen 2006, Kleinmuntz 2007, Marsh et al. 2013). MCDA approaches vary depending on the source and kind of information used during decision-making, but include four common steps: identifying alternatives, identifying evaluation criteria (i.e., attributes), measuring the alternatives against the criteria, and combining the criteria scores using a weighting to produce an overall assessment of each alternative (Marsh et al. 2013). MCDA methods can be divided into three main categories: outranking methods (e.g., ELECTRE, PROMETHEE), goal and reference point methods (e.g., goal programming), and value function methods (e.g., Analytic Hierarchy Process, SMART) (Belton and Stewart 2001).

SMART has been applied to a variety of decision problems in various domains. It is particularly well suited for decision problems where trade-offs between financial and non-financial objectives need to be considered. One of the earliest users of SMART was the Bureau of Reclamation of the U.S. Department of the Interior (Brown and Valenti 1983, Massam 1988). Its Planning Technical Services Engineering Division applied SMART to support the evaluation of plans with multiple impact factors. Another early adopter of SMART was the U.S. military (e.g., Embrey (1981), Loerch et al. (1995)), which is a frequent user to this day (e.g., Taylor and
Love (2014), Parnell et al. (2015)). Further applications of SMART include: infrastructure planning (National Research Council 1996), contaminated site management (Linkov et al. 2006), energy policy (Jones et al. 1990), supplier selection (Birgün Barla 2003), project prioritization (Dutta and Burgess 2003), and construction (Arslan and Kivrak 2008), among many others.

To the best of our knowledge, the use of SMART for capital investment decision at hospitals has not yet been studied in the literature. Corner and Kirkwood (1991) and Keefer et al. (2004) provide a comprehensive survey of applications of decision analysis methods, and also do not report SMART being used to support capital investments at hospitals or other healthcare organizations.

A popular alternative to SMART is the Analytic Hierarchy Process (AHP). AHP determines weights and overall scores through a pairwise comparison of alternatives (Saaty 1988). While popular in practice, it has the major shortcoming that it can lead to rank reversal (Linkov et al. 2006). The addition of an irrelevant alternative or non-discriminating criterion, i.e., a criterion for which all alternatives perform equally well, may cause a reversal in the ranking of alternatives and thus affect the decision (Belton and Gear 1983, Dyer 1990, Pérez et al. 2006, Stewart 1992). AHP and SMART have been compared by Wang and Yang (1998), whose findings suggest that AHP is inferior to SMART from both a theoretical validity as well as predictive performance perspective. Still, AHP has been widely used—including in healthcare—in part because of a popular software called Expert Choice (Ishizaka and Labib 2009). Liberatore and Nydick (2008) provide a comprehensive overview of AHP healthcare applications.

A number of analytical methods have been proposed to solve the technology investment decision problem at hospitals. These approaches include goal programming (Keown and Martin 1976, Wacht and Whitford 1976), economic evaluation (Birch and Gafni 1992, Laupacis 1992),
real options analysis (Levaggi and Michele 2008, Pertile 2009, Wernz et al. 2015), game theory (Levaggi et al. 2009), multiscale decision theory (Deaton et al. 2011, Wernz and Deshmukh 2009, Wernz and Deshmukh 2010, Zhang et al. 2015) and multi-objective optimization (Focke and Stummer 2003). However, most of these mathematical models focus on narrowly defined and idealized decision problems, and have rarely made an impact in practice.

For our proof-of-concept exercise, we assumed that the organization is risk neutral over the range of portfolio outcomes. As Kleinmuntz (2007) states, “risk neutrality implies that only expected values of project costs and benefits are relevant, and that the objective is to maximize expected benefits subject to resource and other constraints.” Accounting for risk in a multi-criteria decision problem is an open research challenge. Current methods are either not practical, or are not normative. For example, “risk adjusting” is a popular technique in practice that however is problematic from a normative standpoint (Kleinmuntz 2007).

3.1. A brief introduction to SMART

SMART was first developed by Edwards (1977) as a method consisting of ten steps, which remained at the core of its practice, even after methodological advances. The ten steps are:

Step 1: Identify the people (decision-makers) whose values should be elicited;

Step 2: Identify the decision(s) that are relevant to the values;

Step 3: Define the list of entities (alternatives) to be evaluated;

Step 4: Identify the dimensions of value (objectives and attributes) for the assessment of the alternatives from Step 3;

Step 5: Rank the dimensions in order of importance;

Step 6: Rate dimensions based on their importance (i.e., assign an importance number to each dimension). First, an importance of 10 is given to the least important dimensions (from the
ranking defined in step 5). Then, the second least important dimension will be assigned a number depending on the ratio between its importance and that of the least important dimension. For example, if the second least important dimension receives an importance rating of 30, this means it is three times more important than the dimension at the bottom of the rank. This process continues until all dimensions are assigned an importance number.

**Step 7:** Sum the importance numbers from Step 6 and divide each by the sum. This percentage will be the normalized dimension’s weight. The sum of all normalized weights must add up to 1.

**Step 8:** Measure the location of each alternative on each dimension and determine its single-dimensional value. This assessment process can range from purely objective to purely subjective. In cases where natural scales or physical measures (Kirkwood 1997) that define the location of each alternative on each dimension (e.g., surface area, or distance from a reference point) exist, the process is objective and nonjudgmental. If those natural scales are not available, the decision-makers’ preferences need to be elicited in order to determine the alternative’s location; the process is then subjective and based on judgment. In direct assessment, decision-makers locate the alternatives on a scale from 0 to 100, where 0 corresponds to the least preferred alternative, 100 to the most preferred, and the remaining alternatives are compared to these two and located accordingly. If direct assessment is used during preference elicitation, the resulting scores can be used as single-dimension values (Goodwin and Wright 2007). Otherwise, further single-dimensional value elicitation methods, such as those provided by Von Winterfeldt and Edwards (1986), can be applied. As a final step, all positions are rescaled to values between 0 and 1.

**Step 9:** Calculate an overall value for each alternative using a weighted average:

\[ V_i = \sum_j w_j v_{ij} \]
where $V_i$ is the aggregate value for the $i$th entity, $w_j$ is the normalized importance weight of the $j$th dimension of value (output from step 7), and $v_{ij}$ is the rescaled position of the $i$th entity on the $j$th dimension (output from step 8).

**Step 10:** Decision makers make a choice based on overall values for each alternative. If there is a budget constraint, the ratios $V_i/C_i$, where $C_i$ is the cost of the $i$th entity, should be used and selected in decreasing order until the budget constraint is met. According to Edwards (1977), the presence of a budget is the only situation that justifies the use of a benefit-cost ratio as a basis to make a decision.

### 3.2. Proof of Concept Implementation

Our proof of concept consisted of two rounds of SMART exercises with students followed by one with Barnabas Health executives. Next, we will discuss the implementation of these exercises.

#### 3.2.1. Student mock exercise

We conducted two mock exercises with students a few months prior to the exercise with Barnabas Health executives with the objective to plan, test, and refine the exercise design. The mock exercises included five to six engineering graduate students each. The participants had different levels of familiarity with decision analysis—from none to some coursework in that domain. None of the student participants had experience with medical technologies; thus, we provided a detailed write-up on each alternative to mimic the knowledge executives would have. We set a specific budget that would make for an interesting portfolio selection challenge.

Participants assessed five investment alternatives plus the Da Vinci Surgical System. These five alternatives were different from those used in the Barnabas Health exercise, since the Barnabas Health investment alternatives were not known at the time. For the student exercises,
we selected medical technologies that would generate interesting trade-off conflicts (e.g., financial vs. quality) among investment alternatives. We chose the Da Vinci surgical system as one of the alternatives, since it is an actively debated technology (Barbash and Glied 2010, Breitenstein et al. 2008, El Nakadi et al. 2006); many hospitals are considering purchasing their first Da Vinci unit, while others are evaluating whether or not to expand or update their current installations (Husain 2010, Lanfranco et al. 2004). We used information from the equipment manufacturers and other literature to describe the investment alternatives features and inform the value elicitation process.

The objectives and attributes were determined based on the findings from our literature review. We used a summary of these objectives and attributes during the student exercises (Table 2).

Insert Table 2 around here

In the first student exercise, we used the weighting method proposed by Edwards (1977). Using this method, decision makers assign an importance number of 10 to the least important objective and rate the other objectives based on their relative importance. For example, an objective that is twice as important would receive the number 20 (see explanation in Section 3.1).

In the second student exercise, we provided objective weights to participants, considering that in practice, these weights are often determined and assessed beforehand by the organizational leadership, rather than by decision makers in charge of allocating the available budget. A sensitivity analysis—described later in Section 3.2.2—helped participants gain insights into the effects of weight changes on the resulting ranking of investment alternatives.
During the first student exercise, we tested different single-dimensional value elicitation methods to gain insight into their applicability. Specifically, we assessed the implementation of both piecewise linear and exponential value functions. We applied the procedure described in Kirkwood (1997), but experienced its implementation as too complex and time consuming. Student participants had difficulties understanding concept of exponential value functions (e.g., mid-value) resulting in a lengthy process, not suited for a time-constrained exercise with executives.

Kleinmuntz (2007) reports similar findings regarding the use of complex value function assessments. He also advocates for the use of direct assessment on all attributes lacking physical measures in portfolio resource allocation problems, as opposed to the elicitation of value functions. Edwards and Barron (1994) also encourage the use of direct assessments because of their simplicity and low likelihood of causing elicitation errors.

The insights we gained during the first student exercise helped us redesign the elicitation of single-dimensional values in the second exercise and in the subsequent exercise with Barnabas Health executives. We describe this process as well as the determination of overall values for investment alternatives and the sensitivity analysis in the next section.
3.2.2. Barnabas Health proof-of-concept

We carried out a SMART exercise with Barnabas Health system-level executives. The Chief Medical Officer (CMO), at the time, Dr. Anthony Slonim selected the participants based on their involvement in the organization’s investment decision-making process. While initially six executives were scheduled, only three could participate due to last minute scheduling conflicts. The three participating executives were in charge of Supply Chain, System Development/Planning and Facilities Management, respectively.

This exercise was a proof of concept because the Barnabas Health’s budgetary situation at the time did not allow for any further investments. For the exercise, we chose a budget of $2.5 million, which would lead to interesting conflicts among investment alternatives. Together with Barnabas Health executives, we selected six medical technologies as investment alternatives in preparation for the exercise. The technologies were chosen from actual prior and current purchase requests, with an emphasis on those that had detailed data (data on the technology is provided by requesting physicians via StrataJazz®). We restricted the number of alternatives to six, since we only were given two hours of meeting time with the executives.

One member of the research team took on the role of moderator and guided the participants through the process. The exercise design adhered to the SMART sequence of steps, and was informed by decision analysis implementation research (e.g., Kleinmuntz (2007)) and practical considerations (e.g., time constraint of executives, lack of familiarity with SMART).

Five out of the six capital investment alternatives evaluated were identified by the Senior Vice President for Facilities Management, and their descriptions were extracted from the StrataJazz® database. The hospital staff that requested the equipment had entered the
corresponding descriptions into the database. We added the DaVinci Surgical System as the sixth alternative. The investment alternatives evaluated were:

1. Big Bore CT Scanner for Radiation Therapy Simulation
2. Mammography Unit
3. Refurbished Mammography Unit
4. Lease Buyout of a 64-Slice Definition CT Scanner
5. Dose Reduction Software for 64-Slice Definition CT Scanner
6. Da Vinci Surgical System

For this SMART exercise, we used the StrataJazz® built-in objectives, following the suggestions of Barnabas Health CMO. These objectives were consistent with the findings from the literature. We defined the corresponding attributes in coordination with the Senior Vice President of Facilities Management, using information available in StrataJazz®. These objectives and attributes (Table 3) were similar to those used in the student exercise.

insert Table 3 around here

The objectives used in the student exercise represented the outcomes of our literature review, whereas the objectives used during the hospital exercise came from StrataJazz®, which in turn is informed by industry best practices. The sets of objectives had overlaps and similarities (e.g., “Financials” and “Financial impact”, “Infrastructure” and “Routine Infrastructure”; “Quality” and “Clinical impact”). Barnabas Health also evaluated investments in light of specific requests from physicians captured by the objective “Staff-physician relationships”.
As in the first student exercise, we used the weighting method proposed by Edwards (1977). Executives rated all five objectives to be equally important, which translated into a weight of 20% each.

As in the second student exercise, we decided to use direct assessment on all attributes, except for net present value (NPV)—the only objective, non-judgmental measure. During the direct assessment process, we used anchor values of 0 and 100 for the least and most preferred alternatives, respectively. This scale facilitates value elicitation, simplifies the arithmetic and is standard decision analysis practice (Goodwin and Wright 2007). We opted to determine the NPV using a linear value function. Participants confirmed that a linear value function is an accurate representation of their preferences.

In the Barnabas Health exercise, one of the attributes evaluated through direct assessment was “impact on treatment options”, which corresponded to the Clinical Impact objective. Since this qualitative attribute lacked a natural scale, we needed to assess its values with a constructed scale. Participants used an anchor value of 0 for their least preferred alternatives (Refurbished Mammography Unit and Lease Buyout of a 64-Slice Definition CT Scanner)—those that would have a minimal impact on treatment options if purchased—and a value of 100 for the alternative they considered would have the largest impact (Big Bore CT Scanner for Radiation Therapy Simulation).

The single-dimensional values of the remaining alternatives were determined based on these two anchor values using an interval scale (Goodwin and Wright 2007). Hospital executives compared the impact on treatment options of the remaining alternatives to the impact of the most preferred alternative, and located them in the interval scale based on these comparisons. For example, the improvement in impact of treatment options between the Refurbished
Mammography Unit and the Dose Reduction Software was perceived to be three times more preferable than the improvement between the Refurbished Mammography Unit and the DaVinci Surgical System (Figure 1).

After obtaining single-dimensional values for all alternatives, an overall value was calculated for each investment alternative using the weighted average method described in Section 3.1. These overall values were then divided by the cost of the corresponding alternative, and the resulting value-cost ratios used to rank the alternatives in descending order. Hospital executives evaluated those ratios and the budget percentage consumed by different investment portfolios. Typically, decision-makers start by selecting alternatives at the top of the ranking until the budget is met. Then they evaluate ways to increase the portfolio’s overall value, for example, trading one of the initial selections with a lower ranked alternative. This analysis is performed until they reach consensus.

To evaluate the robustness of the resulting ranking of alternatives, we performed a sensitivity analysis on the objective weights. In this analysis, we change the importance numbers that decision makers originally assigned to each objective to obtain new weights. The alternatives overall weighted values are then recalculated using the new objective weights, resulting in a new ranking of alternatives. The methodology we used in the exercise with executives and students was as follows:

1. Determine a relevant range of variation for each objective’s weight. Since hospital executives assigned the same importance number to all investment objectives, and thus the
same weight, we used one range of variation for all: -10% to +15% points from the original weight, i.e., 10% to 35%, based on a 20% weight for all objectives.

2. Divide the selected range of variation in intervals of equal length and use these to determine evaluation points. We divided the range from the first step in four intervals of five percentage points each, resulting in six evaluation points: 10%, 15%, 20%, 25%, 30% and 35%.

3. Select one investment objective and one evaluation point. Keeping the importance numbers of all other objectives unchanged, obtain a new importance number for the selected objective and evaluation point using the expression below:

$$S_{jk} = \frac{e_{jk} \times \sum_{i=1}^{n} P_i}{1 - e_{jk}}$$

where $P_i$ is the original importance number of the $i$th objective (i.e., the number assigned by decision makers), $e_{jk}$ is the $k$th evaluation point for the $j$th objective and $S_{jk}$ is the importance number of the $j$th objective that corresponds to evaluation point $e_{jk}$.

4. Repeat the process from Step 3 until all evaluation points for the selected objective are covered, and recalculate the overall value of each alternative using the new weights.

5. Select a different objective and complete Steps 3 and 4 with all investment objectives.

This process helped Barnabas Health executives and student participants understand how the ranking of alternatives would change with varying objective weights. This analysis provides decision makers with a sense of how robust the ranking results are, and is particularly useful in this context because decision makers might disagree or be unsure about the weights.

We used a Microsoft Excel® spreadsheet adapted from Kirkwood (1997) to perform the value analysis process live during exercises. The spreadsheet has several capabilities: recording the assessed values of each alternative on each evaluation dimension (Figure 1), supporting the
assessment of objective weights (Figure 2), performing the calculation of the value for financial impact (or those of any other objective represented by natural scales - Figure 3), determining the weighted single-dimensional and overall values of each alternative (Figure 4), obtaining the corresponding value-cost ratios, ranking the alternatives in descending order and supporting the selection of a budget-constrained portfolio (Figure 5), and performing the sensitivity analysis. We wrote a Visual Basic macro, which carried out all calculations for the sensitivity analysis automatically and displayed the results in a line chart showing the variations on the investment alternatives’ overall values at different evaluation points (Figure 6).

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Insert Figures 2, 3, 4, 5 and 6 around here
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3.2.3. Results and discussion

Exit survey: We developed an exit questionnaire that Barnabas Health executives filled out at the end of the exercise. We sought their feedback on the SMART methodology in general, our implementation, and the moderator’s performance. Out of the three participating executives, only two filled out the survey; this represents a limitation of the quantitative assessment of this study. However, we were able to obtain detailed qualitative feedback from executives during an informal discussion right after the exercise.

On the questionnaire, seventeen questions focused on the methodology itself, three on the moderator’s performance, three on our implementation, and three on the methodology and our implementation simultaneously. Twenty-one questions were formulated as assertions with a five-level Likert scale (Likert 1932) to define the participants’ level of agreement or disagreement,
with two questions requesting further detail on some of the aspects of the methodology and three open questions. Appendix A includes the survey we used with hospital executives.

The questions asked for the executives’ impressions on specific features of SMART, such as the scaling method, objectives and attributes, ranking of alternatives and sensitivity analysis, and on factors that determine its chances of being incorporated into their organization’s decision-making practices, like its intuitiveness, appropriateness given the number of alternatives analyzed regularly, and the amount of time needed to conduct the exercise.

Additionally, we had a discussion with participating executives at the end of the SMART exercise. We received their verbal input and impressions about the method’s structure, the implementation and benefits of our value analysis tool, and its similarities with the StrataJazz® platform capital planning module. They also discussed the viability of SMART as an investment evaluation methodology given their organization’s culture, decision-making practices, and managerial expectations.

Proof-of-concept exercise: The objectives and attributes we found in literature were consistent with those currently used by the StrataJazz® platform (and Barnabas Health). Our compilation of objectives and attributes in Table 1 provides a comprehensive and structured overview of the typical factors considered by healthcare organizations in the evaluation of medical technology investments.

We found direct assessment is efficient and effective in determining the values of objectives lacking natural scales. Moreover, feedback from students and executives confirmed that a linear approximation adequately captures their preferences with respect to financial values. This finding coincides with those reported in the literature (Kirkwood 1997). Our experience during the student exercise showed that a more rigorous value elicitation procedure reduces the
transparency of the judgment exercise, and is in any case more time consuming. Efficient use of
time is especially important when working with executives.

We recommend using the weighting method presented by Edwards (1977) paired with a
sensitivity analysis on the objective weights. This allows decision makers to assess the
robustness of the resulting ranking of alternatives, and triggers further discussion about the
importance of the objectives. The sensitivity analysis we performed helped participants acquire
relevant insight into the features of their particular decision problem, depicting changes resulting
from weight variations. It also ensured the group’s preferences were reflected on the final
ranking of value-cost ratios.

Weight assessment has a small impact on final decision outcomes, as decision-makers’
preferences are already reflected on the alternatives’ scores and final decisions correlate to these
patterns regardless of variations in weights. The sensitivity of decision outcomes to weight
assessment when using linear value functions is low in most cases. This would be problematic if
only one alternative had to be chosen; however, our focus is on the selection of an investment
portfolio, thus this low sensitivity is not relevant.

The student exercises were helpful to confirm the benefits of some SMART
implementation guidelines we found in the literature (e.g., use of a linear approximation to
obtain financial values, anchor values of 0 and 100 during direct assessment), and to identify
those processes that posed difficulties to participants (e.g., use of exponential value functions).
By conducting the student exercises before the exercise with hospital executives, the moderator
was able to measure the amount of time required by each step of the process, and develop an
implementation plan. The written instructions given to participants and value analysis tool were
also modified based on the verbal feedback we obtained from student participants.
The feedback provided by the students and Barnabas Health executives—verbally and through the exit survey—confirmed that SMART is straightforward and easy to understand. They consider simplicity, intuitiveness and flexibility its most significant features. The “Implementation evaluation” section of the exit survey (Appendix A) aimed to determine SMART’s potential of being incorporated to Barnabas Health capital investment decision process. The executives’ answers show they believe SMART can be incorporated into their regular decision-making practices, because the time spent on the exercise was “just right” (i.e., not too long, nor too short), and SMART has the potential of effectively enhancing their current investment decision process given the number of alternatives they analyze and the frequency of their investment analysis meetings (once every two months).

Since the value assessment and sensitivity analysis were performed live during the exercise, decision makers were able to ask questions about each step of the process and get answers from the moderator immediately. This helped participants understand the mechanism behind SMART, how the investment alternatives values are calculated, how objective weights affect the resulting ranking of alternatives, and how robust this ranking is. Performing these analyses live is beneficial to engaging decision makers in the process.

We also found that a hospital would benefit from the implementation of a set of standards or guidelines that ensure the availability of high quality information about the investment alternatives across all objectives. Our experience with Barnabas Health showed that hospital staff addressed different objectives with different levels of detail and completeness when entering the investment alternatives’ characteristics into the StrataJazz® database (e.g., physicians providing detailed information about a CT scanner’s impact on clinical outcomes, but neglecting the market share objective by giving either minimal or no information). This often depends upon the
background of the individual making the capital request. Poorly defined or unclear objectives (e.g., “Routine Infrastructure”) also contribute to this phenomenon and should be avoided.

SMART is an objective framework that is data driven and supports hospital executives’ decisions when accepting or rejecting medical technology requests. In the absence of an objective approach, budget allocation can easily turn political and generate conflicts. Hospital executives found SMART to be a valuable tool to justify their investment decisions, and to defend their decision when confronted by other stakeholders.

3.2.4. Limitations and future directions

The exit survey we distributed among hospital executives was filled out by only two of the three participants, limiting the quantitative assessment of the results. Additionally, the value elicitation phase of SMART might take a large amount of time when a large number of alternatives needs to be evaluated, making the methodology impractical for certain organizations. The typical capital evaluation session includes 40 to 50 requests (Kleinmuntz 2007), and can easily take several hours to complete.

We believe the use of swing weights would be an interesting extension of the method and worth investigating. Since the range of scores given to investment alternatives might influence the objective weights, other approaches such as SMART using Swings (SMARTS) (Edwards and Barron 1994), the Swing Weight Matrix (Parnell and Trainor 2009), and the value increment approach (Kirkwood 1997) should be analyzed and implemented on the medical technology investment decision problem. The Swing Weight Matrix supports a consistent assessment of objective weights by explicitly defining their importance and range of variation in the decision context, and allows decision makers to identify which evaluation measures are not relevant to the decision (Parnell and Trainor 2009). However, we consider that decision makers should be
gradually introduced to the use of these approaches, and that SMART in its basic format can provide them with a good starting point and foundation. In contrast to one-time processes, medical technology investment decision-making is performed repeatedly in most organizations. Decision makers can start using a simple method like SMART, get familiar with it, and later transition and benefit from more sophisticated approaches.

4. Conclusions

This paper documents and analyzes current medical technology decision-making practices in hospitals. We found that the literature provides little information on current practices, and we therefore conducted interviews with hospital administrators to obtain first-hand information. Our findings suggest that significant improvement opportunities for hospitals’ investment processes exist.

Given the opportunities for improvement, we proposed and evaluated the Simple Multi-Attribute Rating Technique (SMART). We evaluated the feasibility and practicality of this approach with a series of proof-of-concept exercises. Two exercises were performed with students, and a third and final exercise with hospital executives at Barnabas Health. Participants were tasked with choosing among six medical technology investment alternatives given a limited budget and a set of organizational objectives.

Our results suggest that SMART can be implemented as a structured and data-driven decision-making approach, transforming the current subjective, informal and ad-hoc practices present in most hospitals. Student participants and executives evaluated SMART as simple, transparent, intuitive, comprehensive, and flexible. Furthermore, executives thought that
SMART can be used in situations with 30-50 investment alternatives, the number which they typically face when making capital investment decisions.

With this paper, we provide practical implementation guidelines for hospitals seeking to apply SMART. In particular, we compared different value elicitation procedures and found direct assessment to be time efficient and decision effective for objectives that lack value-related physical measures (i.e., natural scales). We further found sensitivity analysis of objective weights to be a valuable activity for participants to evaluate the robustness of their ranking of alternatives. Lastly, we compiled a comprehensive list of objectives and attributes that practitioners and researchers can draw from when seeking to systematically assess medical technologies investments in healthcare organizations.

Acknowledgments

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### Tables and Figures

**Table 2: Objectives and attributes presented to students participants**

<table>
<thead>
<tr>
<th>Objective</th>
<th>Description</th>
<th>Attribute(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Financials</td>
<td>The project has a positive financial impact and contributes to an improved financial performance</td>
<td>Net present value in thousand $</td>
</tr>
<tr>
<td>Quality</td>
<td>The project improves accuracy, specificity, reliability, timing, and/or safety of interventions</td>
<td>Degree of quality improvement</td>
</tr>
<tr>
<td>Strategic importance</td>
<td>The project improves the hospital’s market and/or leadership position</td>
<td>Growth in market share</td>
</tr>
<tr>
<td>Infrastructure</td>
<td>The project addresses patients' demand for new/enhanced services and/or increases the hospital's treatment capabilities</td>
<td>Productivity increase (#patients treated/month)</td>
</tr>
<tr>
<td>Ease of implementation</td>
<td>The project's implementation will not disrupt existing operations, equipment/process will seamlessly be incorporated to current processes</td>
<td>Low level of disruption / Usability / Learning curve</td>
</tr>
</tbody>
</table>

**Table 3: Objectives and attributes used with Barnabas Health executives during SMART exercise**

<table>
<thead>
<tr>
<th>Objective</th>
<th>Description</th>
<th>Attribute(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Financial impact</td>
<td>The project increases profitability through higher patient volumes, additional services, additional charge capture, reduced expense, or enhanced productivity</td>
<td>Net present value in thousand $</td>
</tr>
<tr>
<td>Clinical impact</td>
<td>The project improves clinical experience in terms of outcomes, patient safety, waiting times, throughput times, and general comfort</td>
<td>Impact on treatment options</td>
</tr>
<tr>
<td>Market share</td>
<td>The project enhances market share by increasing the number of patients seen or increasing the ability to attract new patients</td>
<td>Growth in volume/Response to competitors’ offers</td>
</tr>
<tr>
<td>Routine infrastructure</td>
<td>The project improves or maintains the quality of the hospital, outside facilities, and equipment. This includes expenditures for safety, code, and accreditation standards</td>
<td>Increase on quality/Allows for accreditation, etc.</td>
</tr>
<tr>
<td>Staff-physician relationships</td>
<td>The project improves the ability of employees and medical staff to work effectively and productively</td>
<td>Increase of trust/Fulfillment of physicians’ requests</td>
</tr>
<tr>
<td>Group</td>
<td>Objective</td>
<td>Attributes</td>
</tr>
<tr>
<td>--------------</td>
<td>--------------------</td>
<td>-----------------------------------</td>
</tr>
<tr>
<td>Financials</td>
<td>Profitability</td>
<td>Return-on-investment</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Reduction in cost per procedure</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Uptime improvement</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Reimbursement</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Cost reduction per patient</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Payback/Payback period (PP)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Discounted PP</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Average Rate of Return (ARR)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Internal Rate of Return (IRR)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Net Present Vale (NPV)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Profitability Index (PI)/Benefit-cost Ratio (BCR)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Accounting Rate of Return (ARR)</td>
</tr>
<tr>
<td>Quality</td>
<td>- Improve accuracy, specificity, reliability, timing, and/or safety of interventions</td>
<td>Mortality</td>
</tr>
<tr>
<td></td>
<td>- Improve operational and maintenance efficiency and effectiveness</td>
<td>Morbidity</td>
</tr>
<tr>
<td></td>
<td>- Maintain (or increase) standardization to improve efficiency</td>
<td>Readmission</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Admission after day surgery for selected tracer procedures</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Return to higher level of care (e.g. from acute to intensive care) for selected tracer conditions and procedures within 48 hours</td>
</tr>
<tr>
<td>Column 1</td>
<td>Length-of-stay reduction</td>
<td>(\text{Length of stay before minus length of stay after the investment or length of stay after divided by length of stay before investment; unit: time units (hours, days, weeks) or percent})</td>
</tr>
<tr>
<td>Column 2</td>
<td>Side effects</td>
<td>Rate of adverse events; unit: percent</td>
</tr>
<tr>
<td>Column 3</td>
<td>Efficacy</td>
<td>Depends on device/procedure</td>
</tr>
<tr>
<td>Column 4</td>
<td>Complication rate</td>
<td>Depends on device/procedure</td>
</tr>
<tr>
<td>Column 5</td>
<td>Results from clinical trials</td>
<td>Depends on device/procedure</td>
</tr>
<tr>
<td>Column 6</td>
<td>Quality of life</td>
<td>e.g. SF-36, SIP, NHP; unit: qualitative scale</td>
</tr>
<tr>
<td>Column 7</td>
<td>Patients’ perception of quality</td>
<td>Average score on overall perception/satisfaction surveys; unit: score</td>
</tr>
</tbody>
</table>

| Strategic importance | -Improve staff retention  
-Retain qualified medical personnel 
-Recruit qualified medical personnel | Level of satisfaction of the caregivers’ team with the environment of care | Maslach Burnout Inventory (MBI, health services version); unit: qualitative scale |
| | Staff’s level of satisfaction with the investment project | Unit: Qualitative scale |
| | Effects on supporting departments | Unit: Qualitative scale |
| | Patients/community’s perception | Results from surveys; unit: qualitative scale |
| | Competitor hospitals’ position on new technology | Other hospitals cover and use the new technology; unit: qualitative scale |
| | Increase/decrease in market share | Difference between current and projected market share, based on number of procedures performed by each hospital and surgeon, or inpatient and outpatient revenues; unit: percentage points |
| | Rate of growth in market share | Projected minus current market share divided by current market share, by projection time horizon, based on number of procedures each hospital and surgeon performed or inpatient and outpatient revenues; unit: percent by time unit (e.g. %/year) |
| | Innovativeness | Degree of innovativeness; unit: qualitative scale |
| | | Depends on device/procedure |
| Infrastructure / Capacity / Access | -Increase patients’ access to care 
-Improve access to quality care 
-Widen the coverage of patient populations and geographical areas | Surgery cancellation | Last minute cancelled surgeries; unit: number of surgeries |
<p>| | Patient waiting times | Sum of all individual waiting times divided by number of patients; unit: time (hours, minutes) |
| | Appointment availability | Days to third next available appointment; unit: days |
| | Influence on resource utilization, utilization rate | Time device is used divided by available time; unit: percent |</p>
<table>
<thead>
<tr>
<th>Category</th>
<th>Description</th>
<th>Unit/Scale</th>
</tr>
</thead>
<tbody>
<tr>
<td>Effect on current service offering or its development</td>
<td>Change in service volume or focus. The technology could be applied on an outpatient basis; unit: qualitative score</td>
<td></td>
</tr>
<tr>
<td>Influence on hospital capacity</td>
<td>Capacity with or without investment; unit: percent</td>
<td></td>
</tr>
<tr>
<td>Productivity increase</td>
<td>Relative increase in number of patients treated per time period (year, month); unit: percent</td>
<td></td>
</tr>
<tr>
<td>Improve community conditions, address patient demand</td>
<td>Community involvement; unit: qualitative scale</td>
<td></td>
</tr>
<tr>
<td>Productivity increase</td>
<td>Community involvement; unit: qualitative scale</td>
<td></td>
</tr>
<tr>
<td>Influence on hospital capacity</td>
<td>Response to community needs; unit: qualitative scale</td>
<td></td>
</tr>
<tr>
<td>Improve community conditions, address patient demand</td>
<td>Patient demand match; unit: qualitative scale</td>
<td></td>
</tr>
<tr>
<td>Improve community conditions, address patient demand</td>
<td>Degree to which current patient demand is met; unit: qualitative scale</td>
<td></td>
</tr>
<tr>
<td>Improve community conditions, address patient demand</td>
<td>Demand and pressure exerted by patients; unit: qualitative scale</td>
<td></td>
</tr>
<tr>
<td>Improve community conditions, address patient demand</td>
<td>Internal research initiatives; unit: qualitative scale</td>
<td></td>
</tr>
<tr>
<td>Improve community conditions, address patient demand</td>
<td>Necessary for supporting multiple research initiatives; unit: qualitative scale</td>
<td></td>
</tr>
<tr>
<td>Improve community conditions, address patient demand</td>
<td>Internal research initiatives; unit: qualitative scale</td>
<td></td>
</tr>
<tr>
<td>Improve community conditions, address patient demand</td>
<td>Necessary for supporting multiple research initiatives; unit: qualitative scale</td>
<td></td>
</tr>
<tr>
<td>Improve community conditions, address patient demand</td>
<td>Internal research initiatives; unit: qualitative scale</td>
<td></td>
</tr>
<tr>
<td>Improve community conditions, address patient demand</td>
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<td></td>
</tr>
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<td>Improve community conditions, address patient demand</td>
<td>Internal research initiatives; unit: qualitative scale</td>
<td></td>
</tr>
<tr>
<td>Improve community conditions, address patient demand</td>
<td>Necessary for supporting multiple research initiatives; unit: qualitative scale</td>
<td></td>
</tr>
<tr>
<td>Ease of implementation</td>
<td>Aim at convenient implementation</td>
<td>Level of disruption; unit: months/days</td>
</tr>
<tr>
<td>Ease of implementation</td>
<td>Incorporation to current operations</td>
<td>Service availability; unit: qualitative scale</td>
</tr>
<tr>
<td>Safety</td>
<td>Medical Equipment Safety, approval by the responsible agency such as FDA; unit: yes/no or qualitative scale</td>
<td></td>
</tr>
<tr>
<td>Usability</td>
<td>User friendliness; unit: qualitative scale</td>
<td></td>
</tr>
<tr>
<td>Upgrades and enhancements</td>
<td>Possibilities to upgrade the equipment or to supplement additional features; unit: qualitative scale</td>
<td></td>
</tr>
<tr>
<td>Training needs</td>
<td>The need for personnel training; unit: qualitative scale</td>
<td></td>
</tr>
</tbody>
</table>
Figure 1: Assessed values of investment alternatives (shown in blue)

<table>
<thead>
<tr>
<th>Alternatives</th>
<th>Financial impact</th>
<th>Clinical impact</th>
<th>Market share</th>
<th>Routine Infrastructure</th>
<th>Staff-Physician Relationships</th>
<th>Costs in thousand $</th>
</tr>
</thead>
<tbody>
<tr>
<td>CT Scanner – Brilliance CT 4D Big Bore for RT simulation</td>
<td>-732.272</td>
<td>100</td>
<td>50</td>
<td>100</td>
<td>100</td>
<td>732.272</td>
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<tr>
<td>Mammography Unit</td>
<td>1318.336</td>
<td>20</td>
<td>75</td>
<td>0</td>
<td>25</td>
<td>468.091</td>
</tr>
<tr>
<td>Mammography Unit – GE essential refurb</td>
<td>-191467</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>25</td>
<td>160</td>
</tr>
<tr>
<td>CT Scanner – Definition CT Lease Buyout (64 slice definition)</td>
<td>-292</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>292</td>
</tr>
<tr>
<td>CT Scanner – Dose reduction software for 64 Slice CT</td>
<td>-191582</td>
<td>60</td>
<td>100</td>
<td>0</td>
<td>25</td>
<td>191582</td>
</tr>
<tr>
<td>Da Vinci Surgical System</td>
<td>454.77</td>
<td>20</td>
<td>20</td>
<td>0</td>
<td>100</td>
<td>2000</td>
</tr>
</tbody>
</table>

Figure 2: Assessment of objective weights

Figure 3: Financial impact’s values
Figure 4: Alternatives’ weighted single-dimensional and overall values

Figure 5: Alternatives’ value-cost ratios, ranking and investment portfolio selection

Figure 6: Results of the sensitivity analysis on the Clinical Impact objective’s weight
Appendix A. Barnabas Health SMART exercise participant survey

Please rate the following statements according to your level of agreement:

<table>
<thead>
<tr>
<th>Methodology evaluation</th>
<th>Strongly disagree</th>
<th>Disagree</th>
<th>Neither agree nor disagree</th>
<th>Agree</th>
<th>Strongly agree</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 I believe the underlying logic of the SMART method is intuitive</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>2a The method is appropriate for the number of projects we, as system-level executives, typically make investment decisions about.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2b Please fill in: We typically consider ___ (number) projects during decision meetings held every ______________ (time frame)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>3 The method could be effectively applied at the system level</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4 The method could be effectively applied at the hospital level</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5 The scaling method for the alternatives (0 to 100) helped to reflect my preferences accurately</td>
<td></td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>6 The objectives were clearly defined in order for me to evaluate each alternative</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7 The performance measures were clearly defined in order for me to evaluate each alternative</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>8 The objectives chosen were comprehensive to inform this decision effectively</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>9 The performance measures chosen were comprehensive to inform this decision effectively</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10a The description of alternatives 1-5 (except DaVinci) contained sufficient information in order for me to assign a meaningful score</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10b The alternative/s that needed to be presented in more detail was/were:</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>11 The ranking of alternatives obtained at the end of the process reflected the group’s preferences</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>12 The ranking of alternatives obtained at the end of the process reflected my own preferences</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>13 I understood the purpose and logic of the sensitivity analysis</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>14 I believe this method accounted for risk appropriately</td>
<td></td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>15 I believe it is worth the time to incorporate additional risk analysis to this method</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
28. Which step of the SMART process was most challenging to you? Please explain.

29. Do you think the SMART decision process can be implemented in your organization? Why or why not?

30. Please provide any additional comments or concerns regarding either the method or how we implemented it during this decision-making session.

31. What additional information would you have liked for the system dynamics to generate?
32. Please provide any additional comments or concerns regarding the system dynamics model shown during the decision-making session.
References


Likert R (1932) A technique for the measurement of attitudes. *Archives of psychology*.


Parnell GS, Trainor TE (2009) 2.3. 1 Using the Swing Weight Matrix to Weight Multiple Objectives, in INCOSE International Symposium, Wiley Online Library, pp. 283-298.


