Improving Technology Investment Decisions at Hospitals Through System Dynamics and Decision Analysis

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Abstract

Medical technologies represent a major share of hospital costs in the United States. Typically, hospitals have limited resources and have to be selective with their purchases. Despite the importance and complexity of investment decisions, most hospitals do not use structured methods or comprehensive data. In response, we developed and field-tested a data-to-decision (D2D) approach. We interviewed executives and physicians from two hospitals to learn about the role of technology and capital investment decision processes. We developed a system dynamics (SD) model for the adoption of a Da Vinci® surgical system. Hospital executives evaluated this technology along with other alternatives in a session we conducted using the Simple Multi-Attribute Rating Technique (SMART).

1. Introduction

Hospitals’ medical technology adoption behavior impacts the ever-rising healthcare costs in the United States (U.S.). For the past 35 years, healthcare spending has increased at an average annual rate of 8.2%, in contrast to a 6.0% Gross Domestic Product (GDP) growth [1]. An estimated 50% of the increase in healthcare spending can be attributed to medical technologies [2, 3]. These technologies affect hospitals’ financial and clinical performance. Patients and physicians constantly demand the latest equipment.

Due to limited financial resources and the high cost of medical equipment, hospitals have to carefully evaluate which items they want to purchase. Decision criteria, besides budget constraints, should be derived from organizational objectives. Typically, these are conflicting factors (e.g., financials vs. clinical impact) with multiple interdependencies, which contribute to the complexity of the investment decision. The decision process is even more challenging when new technologies are being considered, for which data is unavailable or incomplete [4, 5].

Despite the decision complexity, research suggests most hospitals do not use systematic approaches to support this process, which is rather performed ad-hoc and oftentimes driven by favoritism and politics [5]. Healthcare lags behind other industries in the use of rigorous capital investment evaluation methods [6, 7], in part because the decision problem is multi-objective, and standard financial metrics (e.g., net present value (NPV), payback period (PP), etc.) are insufficient.

We developed and field-tested a data-to-decision (D2D) methodology [8], motivated by the industry’s need for a transparent and comprehensive approach to tackle the multi-objective medical technology investment problem [9]. To this end, we interviewed executives and surgeons from two hospitals (referred to as Hospital A and B) to learn about their current decision-making practices and challenges. We built qualitative and quantitative system dynamics (SD) models representing the adoption of the da Vinci® surgical system, our pilot technology, using data and insights obtained during the interviews.

We also implemented the Simple Multi-Attribute Rating Technique (SMART) in a decision-making session with hospital executives, during which they were given a specific budget and evaluated actual capital investment requests along with the da Vinci surgical system. The SD models we developed for this technology were used during the SMART session to further inform the decision-making process.

This paper describes the capital investment evaluation processes at Hospital A and B, and presents the value that our D2D approach can provide to medical technology investment decision-making. Our results confirm that SMART can effectively support this process, and that an SD model offers additional insights to decision makers by projecting the impact of adopting a certain technology on key decision criteria.

The remainder of this paper is structured as follows. Section 2 describes the insights we gained from our interviews with executives from Hospital A and B. In section 3, we explain the qualitative and quantitative SD models we built for the surgical robot. Section 4 gives
an overview of SMART, and describes our implementation as well as our results. We finalize this paper with our conclusions in section 5.

2. Case studies

We conducted semi-structured interviews with executives and surgeons of two different hospitals. They were involved in capital investment decision-making in different capacities (e.g., decision makers, capital requestors). We asked them about their capital investment evaluation and budget allocation processes, technology adoption behavior, and the challenges they face when selecting which medical technologies to purchase.

2.1. Hospital A

From our interviews we learned that this hospital’s financial situation is unique, allowing decision makers to focus primarily on patient care improvement. Unlike most other healthcare organizations, Hospital A has the ability to make large investments, and is not tightly constrained by financial resources.

At the strategic level, decision makers focus on assessing the impact of medical technologies on clinical outcomes and on patient care quality. In fact, these criteria are used as the first selection filter during the capital investment decision-making process. The organization’s strategic goals prioritize patient access and experience, innovation, knowledge acquisition and cutting-edge research. Financial sustainability is also an important concern. Still, patient care is considered the main priority of the organization.

These strategic considerations drive decision-making during the evaluation of major capital investment projects (i.e., more than $2 billion over a horizon of 5+ years). Hospital A has an in-house analytics team that supports capital investment evaluation at both the strategic and operational level. This team is in charge of collecting and analyzing metrics for various factors, such as patient access (e.g., demand, behavioral factors), innovation (e.g., probability of getting grant funding), financials (e.g., cash flows), patient experience (supported by Press Ganey Associates, Inc.), and clinical outcomes.

Despite having a significant spending ability, this hospital performs a data-driven and systematic capital investment evaluation at the operational level, supported by a bottom-up process for the identification of investment alternatives. Each year, different teams within the organization meet with their corresponding leaders and list all their equipment needs. These lists are then consolidated and evaluated by a capital equipment team that performs an initial prioritization. This rank ordering of capital requests responds to different qualitative and quantitative criteria. Qualitative criteria include: patient safety, clinical outcomes, and physician experience and training needs. Some of the quantitative criteria are purchase cost, maintenance cost, infrastructure considerations (e.g., physical space needed), reimbursement, projected case types, and projected case volume. Each department decides which of these criteria will ultimately be used to perform the prioritization.

The executive vice president (VP) of the financial division determines the budget size available for capital investments at each department. Each department’s leadership will then select which capital requests they want to get fulfilled based on this budget, and submit these to the executive finance VP. Final approval is usually given by the end of the calendar year.

Departmental leaders at this hospital invest significant time structuring their capital requests, and rely heavily on quantitative data to justify their capital needs. However, they include both qualitative and quantitative measures to describe the potential impact of medical equipment on the organization’s financial and non-financial performance.

2.2. Hospital B

As in most healthcare organizations, the capital investment decision problem at this hospital revolves around financials. The decision makers we interviewed stated that capital investment evaluation is mainly performed subjectively and is not sufficiently data-driven. This process is not developed in a structured and repeatable way, and rather varies depending on different factors, such as type of technology requested, requestor and purchase cost.

At the strategic level, capital requests that represent critical equipment replacements are prioritized over other investment alternatives. Senior executives then evaluate how capital will be allocated for remaining budget based on criteria such as program expansion needs or business opportunities (e.g., opening new offices, acquisition of physician practices).

Market share is a major consideration for hospital B because of the significant competition in its geographical region. Since medical technologies are an important differentiator in the healthcare marketplace, executives are concerned about their organization’s financial constraints and the limiting effect on market share growth. Trade-offs between necessary replacement investments and growth opportunities are a common challenge in capital investment evaluation, though are often not sufficiently analyzed.

Hospital B uses the enterprise software suite StrataJazz® that includes budgeting, cost accounting, planning and forecasting functions. Physicians and
other hospital staff use this software’s capital planning module to submit their medical technology requests. In some cases, executives refer to this information to either accept or reject equipment requests. However, the capital planning module is mainly used to track the status of previous purchases, and the progress of ongoing projects. Actual decision-making is not supported by metrics that represent the organization’s objectives, and is mainly driven by the judgment and experience of hospital leaders.

Hospital executives frequently raise questions about the life cycles of certain medical technologies. Requestors usually provide their subjective assessments on this matter, and since the hospital does not have a formal method to collect information about the outcomes and performance of previous purchases, executives rely on the opinion of some specialists and their own experience.

3. System dynamics model

We developed qualitative and quantitative SD models showing the factors related to the adoption of the da Vinci surgical system. The da Vinci® is the primary robotic surgery system, with 2,254 units installed in the U.S. as of March of 2015, and operating in approximately 35% of U.S. hospitals [10].

We used the da Vinci as our pilot technology because of its popularity and the complexity of evaluating its effects on all aspects of the organization. Numerous hospitals are considering to buy their first unit, while current users consider updating or expanding their current installations [11, 12]. The da Vinci’s high investment and operating costs, in addition to inconclusive results about the benefits on health outcomes of certain proceedings [13-15], make this a complex investment decision.

3.1. Qualitative model

Based on the information provided by staff from both hospitals, we chose the operational level at the surgery department as the boundary for this model. This allowed us to build an informative model for the investment decision makers. Figure 1 shows the qualitative model we developed.

This model captures some important feedback mechanisms, like the relationship between the capacity of performing robotic and alternative surgeries combined with inpatient and outpatient capacities. Our model also describes how an increase in number of surgeons who use robots can lead to a larger robotic surgery program at the hospital.

As the number of physicians who can operate with surgical robots grows, the number of robotic surgeries grows as well. This cumulative growth also leads to an increase in the hospital’s experience with robotic surgeries. In addition, the cumulative experience contributes to a culture of using robots, and more surgeons who primarily operate with robots are attracted to work with or for the hospital (free agent or employed). More robotic cases trigger a decrease in a patient’s average length of stay at the hospital after a surgery. This reduction leads to an increase in the number of possible surgery cases in the hospital, and thus in the total number of cases.

3.2. Quantitative model

Based on the qualitative model, we developed a quantitative model at the operational and strategic levels (shown in Figures 2a and 2b, respectively). The model consists of four major stock variables: Physicians that have not adopted the robotic surgery technology (Non-adopted Physicians), those that have (Adopted Physicians), Cumulative da Vinci Experience, and the length of stay for patients after going through robotic surgery (Required Stay Perception). We identified these stock variables based on our interviews with physicians and administrative staff from Hospital A and B. Each stock variable captures part of the dynamics behind the robotic system utilization in a hospital.

Acquisition of a robot is a necessary step for starting a robotic surgery program. The development of this program, however, depends on surgeons adopting robotic surgery as an alternative to conventional surgery. This adoption process can be slow or fast, depending on organizational and capacity factors at the hospital. In our model, we take these effects into account by computing demand and capacity, and comparing these two factors for conventional and robotic laparoscopic surgery programs. The effect of word of mouth among surgeons has also been incorporated as part of physicians’ technology adoption rate.

“Cumulative da Vinci Experience” is a stock variable that captures the impact of technology utilization on the experience gained by physicians. As more patients are treated with robotic surgery, the hospital’s robotic program improves. This has two additional effects in our model. First, it affects the hospital’s outpatient-inpatient ratio for surgeries. Second, it has an effect on physicians wanting to perform more robotic surgery cases.

One of the key differences between robotic and conventional laparoscopic surgeries is patient length of stay after the surgery. The robotic program allows physicians to perform more outpatient laparoscopic surgeries, therefore reduces the inpatient surgery load and frees up capacity to perform additional inpatient surgeries. This organizational learning process happens over time, and is modeled as such.
We calculated the demand for four surgery categories—inpatient robotic, outpatient robotic, inpatient conventional, and outpatient conventional—using the number of technology adopting physicians and the cumulative experience of the hospital. Next, we determined the hospital’s capacity on each surgery category using the inpatient, outpatient, and robotic capacities. We obtained the number of surgeries performed in each category by comparing demand and capacity, and closed our causal loops.
We built this model based on physicians’ perspectives, because they play a key role in the development of a robotic surgery program in hospitals. One important mechanism is the effect of experience on the rate at which surgeons choose to perform a laparoscopic surgery using robots. According to the information we gathered during our interviews, a robotic surgeon will start feeling comfortable with the technology after performing 25 surgeries on average, and the learning curve will flatten out after about 50 cases. We have incorporated this information in our model to account for the effect of experience on the surgeons’ performance.

3.3. Results

We present the results of running the quantitative model for a fictional hospital that initially has two surgery robots. We combined and triangulated data from Hospital A and B to fill in data gaps and achieve a comprehensive data basis. Whenever data from both hospitals was available, we opted for Hospital A data.

We considered two scenarios: (1) hospital will keep its two da Vinci robots, and (2) hospital will acquire a new robot in the following year. These two scenarios are compared with each other for a time span of five years. We chose the following as variables of interest: net present value (NPV) of the purchased robot, number of robotic surgeries performed per year, yearly robotic surgery capacity, number of outpatient cases, and ratio of outpatient surgeries to total number of surgeries. Figure 3 shows the trajectories of these variables over a five-year time span.

Our model suggests that purchasing a new robot this year will likely translate into a positive NPV, considering a five-year horizon. As expected, there is a significant increase in capacity, and although the number of cases performed is not expected to reach the new capacity level during the next five years, it is anticipated to have a steady growth. We also observe a smooth but rather slow growth in the number of outpatient surgeries.

3.4. Discussion

Hospitals compete with each other for both patients and physicians. Hospitals try to maximize their market share in terms of patient volume in their geographical region. Moreover, it is crucial for hospitals to be able to attract and keep the best physicians. Physicians are usually most concerned about the quality of care they can provide for their patients, and financial rewards.

Our interviews with executives revealed that besides market considerations, their mission/vision and budgetary situation also affect their decisions. Most hospitals have limited financial resources to invest. If this constraint is removed, hospitals are able to better focus on patient care, and to conduct cutting-edge research if part of their mission.

Hospital executives confirmed that physicians play an important role in identifying medical technology needs and providing input for the decision process. In fact, the role of physicians in this context can be characterized in terms of the principal-agent problem [16-18], i.e., they suggest technologies—which they will use later to provide patient care—as potential investments, while not being directly responsible for the cost of those technologies. Typically, executives rely on physicians to evaluate medical technology and to suggest possible ways of improving patient care.
Financial constraints usually dominate capital investment decisions. State-of-the-art medical technologies are capital intensive. Specifically, da Vinci robots are financially not attractive when only performing inpatient care surgeries. In these cases, hospitals lose money, because diagnosis-related group (DRG) reimbursements currently do not account for the higher cost of robotic surgeries compared to conventional procedures. However, outpatient and their fee-for-service (FFS) reimbursements make da Vinci surgeries profitable to hospitals. Our SD model incorporates this difference and several temporal dynamics in response to insights we gained during interviews with physicians. As a new technology is introduced in a hospital, it has a specific diffusion curve within the organization. For robotic surgery, some surgeons still prefer conventional laparoscopy for the same intervention needs, thus need additional time to adopt the new technology.

New surgeons need to overcome a learning curve to fully master robotic surgery. This learning curve and the hospital’s surgical effective capacity are interdependent. Physicians are more likely to seek training and start using robots if robotic surgery is available at their hospital. Our model also captures the increase in outpatient surgeries as the hospital goes through the technology adoption process.

Our model provided decision makers with an estimation of the NPV, the effective capacity for outpatient procedures, and the number of inpatient and outpatient surgeries (Figures 2a and 2b). The causal relationships captured in the SD model and discussed during the SMART decision-making session helped executives to think systematically about the potential effects of a technology investment. Our model needs to account for future changes in reimbursements and technological advances, which will affect the current attractiveness of a specific technology.

We believe developing a SD model that provides accurate results requires eliciting information from a variety of stakeholders. Even though executives’ perspective was important and guided us in the modeling process, they were only able to provide partial information about the problem. Talking to and
comparing data from multiple stakeholder groups increases modeling reliability and completeness, which is a key criterion good SD models need to satisfy.

4. Decision analysis process

4.1. SMART overview

The Simple Multi-Attribute Rating Technique (SMART) is a multi-criteria decision analysis (MCDA) methodology that was first presented by Edwards [19]. This approach is particularly effective in supporting decision problems including financial and non-financial criteria, and has been applied in numerous areas besides healthcare.

SMART consists of ten steps: 1. Identify decision makers, 2. Identify the decisions, 3. Define the alternatives to be evaluated, 4. Define the objectives and attributes (dimensions) to evaluate the alternatives, 5. Rank the objectives based on their importance, 6. Assign an importance number to each objective, 7. Obtain each objective’s normalized weight dividing its importance number by the sum of importance numbers of all objectives, 8. Determine the location of each alternative on each objective as measured by the corresponding attribute(s), 9. Use a weighted average to obtain an overall value for each alternative, and 10. Decision makers select a group of alternatives based on their overall values. In cases where budget constraints exist, the alternative’s overall value has to be divided by its cost, and the resulting ratio needs to be used to rank the alternatives.

4.2. SMART implementation at Hospital B

We carried out a two-hour decision-making session with three executives from Hospital B. Participants are involved in the capital investment evaluation process on a regular basis. We specified a budget of $2.5 million for the executives to allocate. We chose five investment alternatives from a group of past and current hospital purchase requests with the assistance of one of the participating executives. The da Vinci® surgical robot, our pilot technology, was the sixth alternative under evaluation.

As discussed earlier, Hospital B uses an enterprise software suite to support its planning, budgeting and reporting functions. Physicians and other hospital staff use this software to submit their equipment requests, and executives often refer to this information to assess capital investments. As suggested by the hospital leadership, we used this software’s built-in objectives during the SMART session to facilitate the decision-making process. We identified corresponding attributes from the information given by capital requestors (Table I shows the objectives and attributes used).

We selected the method by Edwards [19] to perform the weighting of objectives. This method instructs decision makers to assign an importance number of 10 to the least important objective and rate the rest based on their relative importance. An objective with an importance of 20 would then be twice as important as the least important objective. Hospital executives assigned the same importance number to all objectives, which resulted in a weight of 20% for each objective.

To determine the alternatives’ single-dimensional values, we applied direct assessment on all attributes except NPV, which we used as a physical, value-related measure. We used 0 and 100 as anchor values for the least and most preferred alternatives. For NPV, we applied a linear value function to determine the alternatives values. Decision makers confirmed a linear value function represented their preferences for money accurately. Other more complex value functions (e.g., exponential, piecewise linear) are difficult to communicate to novice users, and are time consuming in their implementation [20]. The use of direct assessment has been found as overall simpler and less likely to cause preference elicitation errors [21].

We calculated an overall value for each investment alternative using the method described in Section 4.1 (Figure 4), and the corresponding value-cost ratio. These ratios were then used to rank the investment alternatives in descending order. Executives evaluated and discussed these ratios along with the budget consumed by each alternative.

The SD model we built around the adoption of the da Vinci robot was presented to executives to further inform their decisions. Executives asked detailed questions about our modeling assumptions and discussed the impact of purchasing the da Vinci on different metrics like NPV and outpatient surgery capacity, as projected by the SD model. This triggered a deeper assessment of the consequences of this investment compared to the other alternatives that were evaluated using SMART only.

The information we presented during the value elicitation phase of SMART—originally provided by capital requestors—also included assessments on the potential impact of those investments on the hospital’s future performance. These statements were subjective and were not supported quantitatively, which may imply that capital requestors were motivation-biased in their assumptions to document a positive impact of their proposal. The SD model made a difference by offering a graphical representation of the variables behind the projections, their interdependencies, and the mechanisms driving those projections.
Table 1. Objectives and attributes used in SMART session

<table>
<thead>
<tr>
<th>Objective</th>
<th>Description</th>
<th>Attribute(s)</th>
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<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>
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Figure 4. Weighted single-dimensional and overall values for investment alternatives

Figure 5. Value-cost ratios, ranking of alternatives, and portfolio selection

Figure 6. Sensitivity analysis results – Market Share objective’s weight
Since all these were explicitly presented to the decision makers, they were able to perform a more thorough analysis of the da Vinci investment. After evaluating all six alternatives, executives selected a portfolio that met the budget constraint (Figure 5).

We performed a sensitivity analysis around the objectives weights to determine the robustness of the ranking of investment alternatives. We changed the original importance numbers of each objective (i.e., those assigned by executives) to obtain new weights. We then recalculated the alternatives overall values using the new objective weights, which lead to a new ranking of alternatives. Figure 6 shows the results of the Market Share sensitivity analysis.

4.3. Results

We developed an exit survey to collect participants’ feedback on our SD model, SMART, and our implementation. Even though only two out of the three participants filled out the survey – limiting our quantitative evaluation of this study – we obtained rich qualitative feedback during a discussion with executives after the session.

Regarding our implementation of SMART, we found direct assessment to be useful when obtaining the values of objectives without physical measures. A linear value function is well suited for financial values. These practices have shown to work well in decision exercises with time constraints because of their simplicity and transparency. We suggest using the weighting method by Edwards [19] along with a sensitivity analysis on the objectives weights. This way decision makers are able to analyze changes in value-cost ratios and ensure the final ranking of alternatives reflects their preferences.

Hospital executives found SMART simple and easy to understand, and commended its transparency, flexibility and intuitiveness. They believe that it can be used to support their current investment decision-making process, and is appropriate for the frequency of their meetings (about every two months) and the number of alternatives they evaluate (40-50).

We found that the information provided by capital requestors about the investment alternatives varied greatly in terms of detail and completeness. This might have been caused by differences in the requestors’ background, or their experience and insights on how the depth and quality of information may positively affect the decision in their interest.

Participants valued the additional insights provided by the SD model. The mechanisms presented raised many questions and helped them understand the various effects of purchasing and adopting a new technology. Participants were also eager to learn more about the specifics behind the phenomena shown.

One of the limitations of our work lies in the short duration of the decision-making exercise. If a large number of alternatives need to be evaluated, a SMART session can require a considerable time commitment by executives. Lastly, and as mentioned before, the number of survey responses we obtained limits our quantitative assessment of this work.

The use of swing weights is a potential extension of our research. Given that the range of scores assigned to investment alternatives can affect the objectives weights, other MCDA approaches such as SMART using Swings (SMARTS) [21] and the Swing Weight Matrix [22] can be applied to this problem. Since medical technology investment evaluation is typically a repeated process, decision makers could start using SMART to get familiar with the basic MCDA steps. More complex methods may be introduced as decision makers become familiar with the basic method.

5. Conclusions

This paper describes the development of a data-to-decision (D2D) approach for the medical technology investment decision at hospitals. We partnered with two hospitals to structure and field-test this method. We conducted interviews with executives and physicians from these hospitals. These interviews revealed significant differences in their approach to budget allocation and medical technology investment decision-making.

Hospital A presents a unique financial situation that allows decision makers to focus on improving clinical care. Therefore, budget availability is not a major constraint and capital investment evaluation resembles a single-criterion decision problem (maximize quality). Moreover, this hospital’s decision process is structured and data-driven, supported by an in-house analytics team.

Hospital B represents the budgetary situation of most healthcare organizations: financial resources are limited and only some medical technology requests can be fulfilled. The executives we interviewed mentioned medical technologies are evaluated subjectively and decision-making responds to varying but not rigorously defined or consistent criteria.

We developed an SD model for technology adoption of the da Vinci® surgical robot. Our model showed that purchasing a da Vinci could be a justifiable investment decision if accompanied by other conditions such as an expansion of the outpatient surgery program in a given hospital. To provide
decision makers with relevant insights, this model needs to be calibrated with the hospital data. Our SD model provides a starting point and basis for developing models for other medical technologies.

We carried out a capital investment decision-making session using SMART where hospital executives evaluated actual capital investments along with the da Vinci robot under a budgetary constraint. Our results suggest that SMART can be implemented as a systematic and objective methodology in this and other hospital organizations, and replace the informal and ad-hoc decision process. Our implementation approach can be helpful to healthcare organizations that want an objective and data-driven method for their capital investment decisions.

From the results of our SMART implementation case study, we recommend using direct assessment on all objectives lacking value-related physical measures. We performed a sensitivity analysis about the objectives weights to determine the robustness of the ranking of investment alternatives. This further informed decision-making and triggered a deeper discussion among participants.

Hospital executives gave us positive feedback regarding SMART. They considered it flexible, transparent, and intuitive. Given the frequency of this decision and the number of investment alternatives they typically evaluate, our findings suggest that it can be regularly applied in capital investment evaluations. Executives confirmed that SMART gave them valuable insights about their decision problem, and helped them making a final representing their preferences and the hospital’s strategic objectives.

References