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Hospital Profitability of Robot-Assisted Gastrointestinal Cancer Surgery in Japan Under the National Fee Schedule: A Surgical Program Model with Required-Cut and Isoprofit Maps

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Abstract

Background/Objectives: Robot-assisted gastrointestinal (GI) cancer surgery has expanded in Japan since national reimbursement in 2018, yet hospital profitability remains uncertain because of capital, maintenance, and consumable costs. We examined whether a program-level volume threshold for profitability exists under Japan's fee schedule and quantified actionable improvement targets. Methods: We developed a hospital-perspective, model-based economic evaluation (index admission to 30 days; 2025 Japanese yen (JPY)) comparing robot-assisted surgery (RAS) with conventional laparoscopic surgery (CLS) under Japan's fee schedule (one point = ¥10) for gastrectomy, colectomy, rectal resection, and pancreatoduodenectomy. Case-level contribution margin differentials (ΔCM) were defined as the revenue differential minus the consumables differential and additional operating room (OR) time costs, plus savings from reduced length of stay (LOS), and were aggregated to annual program profit (Π) after fixed costs and platform sharing. Primary outputs were allowable consumables, required cut (%), and isoprofit contours. Uncertainty was assessed using 50,000-iteration probabilistic sensitivity analysis (PSA), one-way sensitivity analysis (OWSA), and learning-curve scenarios in line with Consolidated Health Economic Evaluation Reporting Standards (CHEERS) 2022. Results: In the base case, ΔCM was predominantly ≤0 for colon, rectum, and pancreatoduodenectomy; therefore, when the case-mix-weighted mean ΔCM was ≤0, increasing volume could not achieve breakeven and instead increased losses. Each 10 min reduction in OR time increased allowable consumables by ¥15,000, and each bed-day reduction increased it by ¥30,000. These required-cut and isoprofit maps provide actionable targets for cost negotiation, operational improvement, and platform sharing. Conclusions: Volume expansion alone rarely yields profitability; coordinated reductions in consumables, OR time, and LOS, together with platform sharing, are required.

Keywords: robot-assisted gastrointestinal cancer surgery; hospital perspective; robotic gastrectomy; robotic colectomy; budget impact analysis; costs and cost analysis; fee-for-service; Japan

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1. Introduction

1.1. Background

Robot-assisted surgery (RAS) is growing in gastrointestinal (GI) surgery. In Japan, it has been nationally reimbursed since April 2018, and case volumes have concurrently increased with facility and surgeon credentialing [1]. However, RAS entails significant capital and maintenance expenses along with considerable consumable costs, making hospital-level profitability a key factor in adoption decisions. Under Japan's uniform national fee schedule (a fee-for-service system where one point equals ¥10), procedure-specific K-code points directly determine revenue [2,3].

The fee schedule favors gastrectomy, where RAS use is explicitly assigned higher points, whereas colectomy and pancreaticoduodenectomy generally lack RAS-specific add-ons—resulting in a procedure-dependent, exogenous revenue differential [4,5]. Clinical outcome evidence is mixed: the ROLARR randomized trial showed no superiority in key endpoints for rectal cancer [6], whereas the REAL trial reported improved short-term outcomes and resection quality for mid- to low-rectal cancer with RAS [7]. Japanese real-world analyses using the nationwide Diagnosis Procedure Combination (DPC) inpatient database found lower rates of surgical-site infection (SSI) and respiratory failure in rectal cancer; although intraoperative costs were higher, total costs were overall comparable and reduced in low anterior resection in one study [8,9]. Therefore, clinical benefits do not automatically result in positive margins for hospitals.

This study does not evaluate oncologic radicality, long-term outcomes, or clinical superiority of robot-assisted surgery. Instead, it assumes clinical acceptability based on published evidence and focuses on hospital financial sustainability under Japan's national fee schedule.

These characteristics motivate a hospital-focused, model-based evaluation that clarifies reimbursement regulations and cost structures while comparing RAS with conventional laparoscopic surgery (CLS). We evaluate the presence of a volume threshold for hospital profitability and identify actionable factors—consumables pricing, operating room (OR) time, length of stay (LOS), and platform sharing with other departments—to guide adoption and governance, in compliance with Consolidated Health Economic Evaluation Reporting Standards (CHEERS) 2022 reporting standards [10].

For GI surgeons, decisions to adopt or scale RAS programs are taken in the context of multidisciplinary tumor boards and departmental meetings, where potential advantages in pelvic dissection, nerve preservation, and lymph node dissection must be balanced against constraints in operating room time, staffing, and ward capacity. In practice, heads of GI surgery are asked to justify investment in robotic platforms, define indications, and design learning-curve pathways while coordinating block scheduling with other departments such as urology and gynecology. To support these surgical decisions, an explicit link between clinical pathways and program-level profit–loss is required so that surgeons and managers can discuss case selection, training, and platform sharing on a common financial basis.

1.2. Objectives

1.2.1. Primary Objective

We develop a hospital-centric, model-based evaluation within Japan's fee schedule (K-codes; one point = ¥10) [2,3] to quantify the conditions under which GI RAS outperforms CLS in (i) case-level contribution margin (ΔCM) and (ii) annual program profit (Π), with a primary focus on the existence of a profitability volume threshold. Reporting conforms to CHEERS 2022 [10], and model design, uncertainty analysis, and validation adhere to the International Society for Pharmacoeconomics and Outcomes Research

(ISPOR)–Society for Medical Decision Making (SMDM) Modeling Good Research Practices [11–14]. The framework is explicitly tailored to support GI surgical departments when planning adoption, scaling, or discontinuation of RAS programs.

1.2.2. Secondary Objectives

1. Estimate the distribution of ΔCM for each procedure and analyze contributing factors.
2. Calculate and illustrate the necessary percentage reduction in consumables differential to achieve (a) case-level allowable consumables and (b) program-level allowable consumables after fixed costs $(1 - r)F$.
3. Depict isoprofit contours ($\Pi = 0$) across annual volume (N), platform-sharing rate (r), and fixed cost (F) to define feasibility regions.
4. Define productivity indicators that convert reductions in operative time (Δt) and length of stay (ΔLOS) into monetary values per OR minute and per bed-day, consistent with time-driven activity-based costing (TDABC)/OR-cost frameworks [15,16].

2. State of the Art and Novelty

This section summarizes prior clinical and economic evidence on GI RAS and clarifies the gap that motivates the present hospital-perspective program model.

2.1. Evidence on Clinical Outcomes and Implementation in Japan

Since national reimbursement began in 2018, GI RAS has expanded in Japan with facility and surgeon credentialing [1]. Clinical outcome evidence is procedure-dependent: the ROLARR randomized trial did not demonstrate clear superiority for rectal cancer in key endpoints [6], whereas the REAL trial reported improved short-term outcomes and resection quality for mid- to low-rectal cancer [7]. Japanese real-world studies using nationwide inpatient data also report differential complication profiles, while perioperative costs remain higher for robotic approaches [8,9].

2.2. Evidence on Costs and Hospital Profitability

Systematic reviews and economic evaluations commonly report higher procedure costs for robotic approaches compared with laparoscopy, even when some perioperative outcomes improve [17–20]. For gastric surgery, umbrella reviews and comparative studies similarly suggest mixed clinical advantages with persistent incremental costs attributable to consumables and OR time [21,22]. In Japan, analyses focused on hospital accounting have highlighted lower gross profits for robotic programs relative to laparoscopy, underscoring the importance of consumables, fixed costs, and cost-allocation rules [23]. Translating time and bed days into monetary terms is typically supported by TDABC and OR cost frameworks [15,16], and the valuation of LOS can be interpreted using either accounting or opportunity–cost perspectives [24,25].

2.3. Gap and Novelty of the Present Study

Despite this growing literature, decision-makers in Japanese fee-for-service hospitals still lack an implementation-oriented model that explicitly links Japan's procedure-specific fee schedule differentials with the main controllable levers of a robotic program—consumable pricing, OR time, LOS, and platform sharing across departments. The novelty of this study is to (i) formalize case-level contribution margin differentials and aggregate them to annual program profit after fixed costs and platform sharing, (ii) derive actionable thresholds (allowable consumables and required cut (%)), and (iii) visualize feasibility

using required-cut maps and isoprofit contours, including the condition under which no volume threshold exists. The subsequent Methods section operationalizes these aims.

3. Methods

3.1. Research Design and Workflow

We employed a six-step workflow (Figure 1) to link the study objectives to the analyses and outputs.

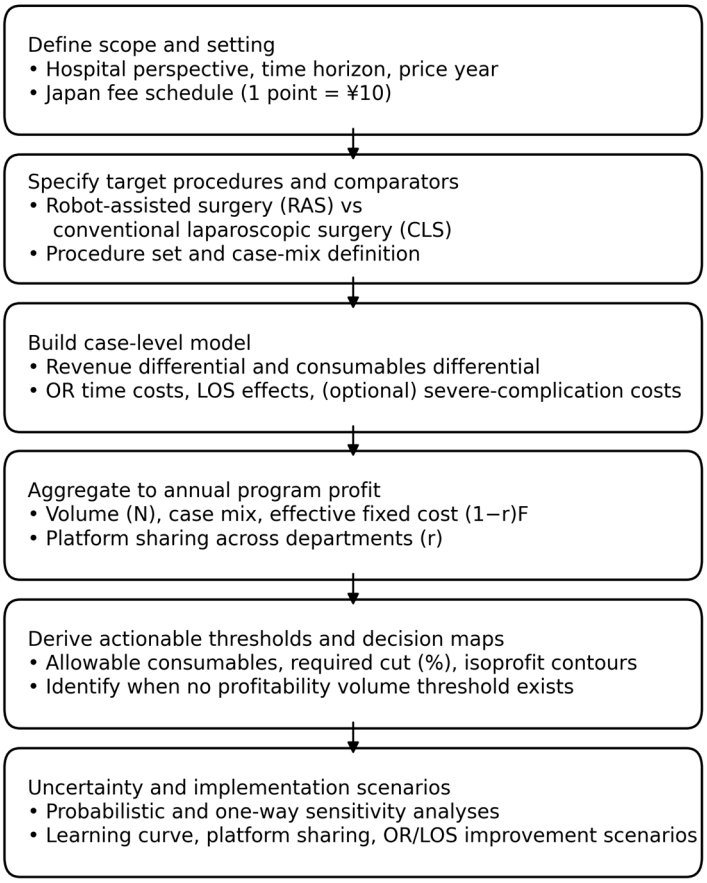

Figure 1. Research design and analytical workflow. The study followed a sequential workflow: defining scope and setting (hospital perspective, time horizon, price year, and Japan's fee schedule), specifying target procedures and comparators (robot-assisted surgery (RAS) vs. conventional laparoscopic surgery (CLS)) and case mix, building the case-level model incorporating revenue and consumables differentials with operating room (OR) time costs, length-of-stay (LOS) effects, and optional severe-complication costs, aggregating to annual program profit accounting for annual volume (N), effective fixed cost (1 − r)F, and platform sharing (r), deriving actionable thresholds and decision maps (allowable consumables, required cut (%), and isoprofit contours) including conditions with no profitability volume threshold, and evaluating uncertainty and implementation scenarios using probabilistic and one-way sensitivity analyses with learning-curve and platform-sharing scenarios. Abbreviations: RAS, robot-assisted surgery; CLS, laparoscopic surgery; OR, operating room; LOS, length of stay; N, annual volume; F, annual fixed cost; r, platform-sharing rate.

1. Define the decision setting (hospital perspective, time horizon, price year, and Japan's fee schedule (1 point = ¥10)).

2. Specify target procedures and comparators RAS vs. conventional laparoscopic surgery (CLS) and treat procedure-specific fee-schedule revenue differentials as fixed inputs.
3. Build the case-level model for the contribution margin differential (ΔCM) using consumables, OR time, LOS, and (in scenario analyses) severe complications.
4. Aggregate procedure-specific results by annual volume and case mix to compute annual program profit (Π), accounting for fixed costs and platform sharing.
5. Derive decision thresholds (allowable consumables and required cut (%)) and visualize feasibility using required-cut and isoprofit maps.
6. Characterize uncertainty using probabilistic sensitivity analysis (PSA), one-way sensitivity analysis, and learning-curve scenarios.

3.2. Study Setting, Perspective and Scope

This section defines the decision setting, target procedures, time horizon, and price year used in the hospital-perspective program model, along with the reimbursement rules that determine the exogenous revenue differential between RAS and CLS.

- **Perspective.** Hospital (provider): Costs are assessed using internal hospital metrics, including per-minute OR costs c_{OR}, per-day bed costs c_{bed}, consumables, and other supplies. Revenues are calculated based on Japan's uniform fee-for-service schedule (K-codes; 1 point = ¥10) [2].
- **Target procedures.** Gastrectomy—distal gastrectomy (DG), total gastrectomy (TG), and proximal gastrectomy (PG); colectomy—right hemicolectomy and sigmoidectomy; rectal resections—low anterior resection (LAR) and abdominoperineal resection (APR); local duodenal resection; and pancreatoduodenectomy (PD). Comparator: RAS versus CLS.
- **Revenue (fee-schedule differential).** Revenue differences are determined by fee-schedule differentials. Major gastric procedures incorporate explicit RAS lines (endoscopic surgical support system) with higher points (e.g., K655-2 RAS 73,590 points; K655-5 RAS 80,000 points; K657-2 RAS 98,850 points), whereas colectomy (K719-3) and PD (K703-2) generally lack RAS-specific add-ons [4,5]. This heterogeneity in procedure-level revenue is treated as exogenous in the model.
- **Time horizon.** From index admission through 30 postoperative days for hospital costs and revenues; a 90-day scenario is evaluated in sensitivity analysis.
- **Currency and price year.** Japanese yen (JPY), 2025 price year; no discounting was applied due to the short time horizon.
- **Reporting standards.** CHEERS 2022 [10]. An item-by-item correspondence to the CHEERS 2022 reporting standard is provided in Table A1 (Appendix A).
- **Modeling conventions.** ISPOR–SMDM Modeling Good Research Practices were adhered to for model design, parameterization, uncertainty, transparency, and validation [11–14].

3.3. Model Structure and Equations

3.3.1. Notation, Units, and Equations

Notation and units (sign conventions in italics):

- ΔRev_s [JPY/case]—Fee-schedule point difference (RAS − CLS) × ¥10.
- ΔCons0_s [JPY/case]—Consumables/supplies differential (RAS − CLS). ΔCons0_s denotes the current observed differential.
- c_{OR} [JPY/min]—OR cost per minute.
- c_{bed} [JPY/day]—Inpatient bed cost per day.
- Δt_s [min; RAS − CLS]—Operative-time difference (positive if RAS is longer).

- ΔLOS_s [days; CLS − RAS]—Length-of-stay difference (positive if LOS is shorter with RAS).
- $\Delta Comp_{i,s}$ [JPY/case]—Additional severe-complication cost differential (e.g., Clavien–Dindo ≥ III). Base case: 0 if costs are already mediated via ΔLOS; included explicitly only in sensitivity analysis.
- F [JPY/year]—Annual fixed cost of the robotic platform (depreciation + maintenance).
- r [0–1]—Platform-sharing rate with other departments; effective fixed cost for GI surgery is (1 − r)F.
- N [cases/year]—Annual GI-RAS program volume.
- N_s [cases/year]—Annual number of GI-RAS cases for procedure s; $N = \Sigma_s N_s$.
- w_s [0–1]—Case-mix weight for procedure s, defined as $w_s = N_s/N$.
- Π [JPY/year]—Annual program profit.

Overview of the model. We first define the per-case contribution margin differential (ΔCM) between RAS and CLS (Equation (1)). We then aggregate procedure-specific margins over annual case volumes (N_s) to obtain annual program profit (Π), subtracting the effective fixed cost of the robotic platform after sharing (Equation (2)). Equations (3) and (5) rearrange Equations (1) and (2) to yield actionable thresholds—allowable consumables and the required cut (%)—that translate feasibility into contracting and operational targets. Finally, we model learning-related reductions in operative time using an exponential decay function (Equation (6)) to explore implementation trajectories.

3.3.2. Case-Level Profit-and-Loss Differential

For procedure s and case i, the case-level contribution margin differential (RAS − CLS) is defined as

$$\Delta CM_{i,s} = \Delta Rev_s - \Delta Cons_{i,s} - c_{OR}\,\Delta t_{i,s} + c_{bed}\,\Delta LOS_{i,s} - \Delta Comp_{i,s} \quad (1)$$

where $\Delta Cons_{i,s}$ denotes the consumables differential for case i, procedure s; in the base case, it is assumed equal to the current procedure-specific value $\Delta Cons0_s$, i.e., $\Delta Cons_{i,s} \equiv \Delta Cons0_s$. In the probabilistic sensitivity analysis (PSA), $\Delta Cons_{i,s}$ is assigned a distribution (e.g., log-normal) and sampled to represent case-level variability primarily reflecting price fluctuations, inter-facility heterogeneity, and the width of uncertainty.

The severe-complication cost term $\Delta Comp_{i,s}$ represents the additional cost differential for Clavien–Dindo ≥ III. When such costs are considered already accounted for through ΔLOS, they are set to zero in the base case. Since multivariable regression on Japanese real-world data (RWD) did not identify a significant contribution to ΔLOS, the base case sets $\Delta Comp_{i,s} = 0$, with $\Delta Comp_{i,s} > 0$ examined in sensitivity analysis.

ΔRev_s: Revenue differential from K-code points (RAS − CLS; point difference × ¥10) (approximately zero for colon and PD, positive for stomach) [4,5].

$\Delta Cons0_s$: Consumables/supplies differential (RAS > CLS).

c_{OR}: OR cost per minute (includes personnel, expendables, and depreciation equivalents) [15,16].

$\Delta t_{i,s}$: Operative-time difference (minutes).

c_{bed}: Inpatient bed cost per day.

$\Delta LOS_{i,s}$: LOS difference (days; CLS − RAS; a reduction is positive).

$\Delta Comp_{i,s}$: Additional cost differential for severe complications such as Clavien–Dindo ≥ III (explicitly included as necessary; set to zero when considered encompassed by the LOS difference) [11–14].

3.3.3. Annual Program Profit and Volume Threshold

The annual program profit (JPY/year) is defined as

$$\Pi = \sum_{i=1}^{N} \Delta CM_{s(i),i} - F_{eff}, \quad F_{eff} = (1-r)F \tag{2}$$

where F denotes the annual fixed cost, r indicates the platform-sharing rate with other departments, and N represents the annual volume of the GI RAS program.

The term $\Delta CM_{s(i),i}$ represents the sum of profit and loss at the case level; as previously described, each ΔCM is calculated by combining the revenue (K-code point difference), additional consumables costs, costs from extended operative time, and savings from a shorter LOS, among others. The sharing rate r is defined by the actual share-of-use (e.g., urology, gynecology) or by internal allocation rules, and (1 − r)F is referred to as the effective fixed cost F_{eff}. It represents the portion of the robot's annual fixed costs that are not distributed to other departments through cost-sharing, thereby remaining the responsibility of the focal department (GI surgery).

Therefore, as the number of cases N increases, the average profit or loss per case $\overline{\Delta CM}$ aggregates, and profitability hinges on whether the total covers the effective fixed costs. By employing the case-mix-weighted mean per-case value w_s, we can express $\Pi = N \cdot \overline{\Delta CM} - (1-r)F$, $\overline{\Delta CM} = \sum_s w_s \, E[\Delta CM_s]$. For program-level visualizations, we use an illustrative case-mix scenario and treat w_s as fixed while varying N.

This introduces the concept of a volume threshold: if the average per-case profit or loss is positive, performing a minimum number of cases allows the program to recoup its fixed costs. Conversely, if the average per-case profit or loss is negative, increasing the number of cases will not only fail to cover the fixed costs but also worsen the deficit; in such situations, we define that no volume threshold exists. Formally, while keeping other parameters fixed at their base-case values, a volume threshold exists if and only if there is a smallest integer N* such that $\Pi \geq 0$.

This condition holds only when $\overline{\Delta CM} > 0$, in which case $N^* = \lceil (1-r)F / \overline{\Delta CM} \rceil$.

If $\overline{\Delta CM} \leq 0$, no volume threshold exists.

3.3.4. Case-Level Allowable Consumables and Required Cut (%)

We first determine, for each procedure s, the upper bound of the consumables differential that can generate a surplus. Because case-level surplus requires $\Delta CM_s \geq 0$, it follows that $\Delta\text{Rev}_s - \Delta\text{Cons}_s - c_{OR}\,\Delta t_s + c_{bed}\,\Delta\text{LOS}_s\,(-\Delta Comp_s) \geq 0$, and hence, $\Delta\text{Cons}_s \leq \Delta\text{Rev}_s - c_{OR}\,\Delta t_s + c_{bed}\,\Delta\text{LOS}_s\,(-\Delta Comp_s)$.

$\Delta\text{Rev}_s - \Delta\text{Cons}_s - c_{OR}$. Therefore, the per-case upper bound of the consumables differential required to achieve a surplus is

$$\Delta\text{Cons}_s^{\star} = \Delta\text{Rev}_s - c_{OR}\,\Delta t_s + c_{bed}\,\Delta\text{LOS}_s\,(-\Delta Comp_s) \tag{3}$$

Achieving a surplus, in principle, requires accumulating cases whose consumables differentials do not exceed the per-case upper limit. However, hospital accounting must also consider the annual fixed costs of the robotic platform, including depreciation and maintenance. Recovering the platform cost at the annual program level establishes a more stringent criterion. Utilizing the effective fixed cost, the upper bound including fixed costs at the program level is

$$\Delta\text{Cons}^{\star}_{\text{program}} = \Delta\text{Cons}^{\star}_{\text{case}} - \frac{F_{eff}}{N} \tag{4}$$

When the current consumables differential exceeds this upper bound, managerial feasibility is not evaluated based solely on that fact. Instead, an indicator is employed to represent the percentage reduction required in the current consumables differential to meet the bound. This indicator is referred to as the required cut. Let ΔCons0_s denote the current consumables differential; then the required cut (%) is calculated as

$$\text{Required cut} = 1 - \frac{\Delta Cons^{\star}}{\Delta Cons0_s} \quad (5)$$

If the required cut is 0%, the current cost precisely aligns with the upper bound, and no further reduction is necessary to achieve a surplus. A required cut of 50% signifies that the current cost must be halved. A required cut ≥ 100% indicates that breakeven is theoretically unattainable at the case level. Therefore, the required cut quantifies the necessary reduction rate for profitability, establishing clear targets for price negotiations and cost-reduction initiatives, and elucidating the scope and feasibility of reductions by procedure. Scenario analyses can incorporate improvements in time and LOS alongside cost compression. In unit terms, each 10 min saved in the OR increases the allowable differential by $10 \times c_{OR}$ JPY, and each inpatient day saved increases it by c_{bed} JPY [15,16]. For example, if $c_{OR} = 1500$ JPY/min, this is ¥15,000 per 10 min; if $c_{bed} = 30{,}000$ JPY/day, this is ¥30,000 per day.

3.3.5. Learning Curve and Capacity

The operative-time difference (Δt) has previously been treated as a constant; however, it is known to decrease steadily as cumulative case volume increases. As the surgeon and team gain experience, OR utilization efficiency improves, and the per-case time difference diminishes.

This learning effect directly enhances the case-level profit-and-loss differential $\Delta CM_{i,s}$ while also increasing the annual case capacity (N). In other words, because the learning curve contributes to hospital-level profit through two pathways—improving time difference and expanding the case ceiling—it must be incorporated into the model. Accordingly, $\Delta t_{i,s}$ may depend on elapsed experience (cumulative cases $\text{Cum}N_{i,s}$) via a learning curve. Therefore, we incorporate an exponential-decay model as a scenario,

$$\Delta t_{i,s} = \Delta t_{0,s}\, e^{-k_s\, CumN_{i,s}} + \varepsilon_i \quad (6)$$

where k_s denotes the procedure-specific learning rate and ε_i indicates a residual term. The learning effect influences thresholds through the improvement of the objective function Π [11–14]. For k_s, we base assumptions on prior reports (e.g., in robotic rectal cancer surgery, a halving case count of approximately 40–60 cases), set a base value of k_s accordingly, and impose a residual floor for Δt of approximately 10–15 min. Residuals are assumed to follow a normal distribution [26].

3.3.6. Simultaneous Procedures and Postoperative Mortality Scenarios

Combined (simultaneous) procedures can increase both consumables and operative time beyond the index resection. To reflect this real-world situation, we evaluate a simultaneous-procedure scenario by adding procedure-specific increments to the base differentials (ΔCons and Δt) before applying Equation (1). The increments are treated as scenario inputs because they depend on local case selection and coding rules.

Postoperative mortality is rare but can be associated with high resource use (e.g., intensive care unit care). Because many of these costs are mediated through length of stay and major complications, mortality is not modeled as a separate base-case endpoint. Instead, the model allows an optional mortality-related cost to be incorporated as part of ΔComp (Equation (1)) when it is a local concern; however, we do not assign a single base-case value or a fixed national range because mortality attribution and end-of-life resource use vary markedly across institutions. Mortality-cost scenarios should therefore be parameterized using site-specific accounting and clinical pathway assumptions.

3.4. Input Parameters (Effects, Costs, and Revenues)

3.4.1. Revenues (Fee-Schedule Differential)

Gastrectomy (DG/TG/PG). RAS is explicitly awarded higher points (e.g., K6552: 73,590 points; K6555: 80,000 points; K6572: 98,850 points) [4].

Colon (K7193), rectum, and PD (K7032). No RAS-specific add-on (same frame as CLS) [4,5].

Accordingly, ΔRev_s is treated as a procedure-specific constant [2,4,5]. Device- and hospital-level constants are summarized in Table A2 (Appendix B), and procedure-specific inputs are provided in Table A3 (Appendix B).

3.4.2. Effect Sizes (Δt, ΔLOS, and Complications)

Sources and synthesis. We extract procedure-specific differentials (RAS − CLS) from randomized controlled trials (RCTs; ROLARR, REAL) and Japanese RWD sources, including the nationwide DPC inpatient database and the Medical Data Vision (MDV) database. Priors are estimated using hierarchical Bayesian meta-regression, stratified by procedure and study design (RCT/RWD) [6–9,11–13].

Endpoints. Δt (min): Allows for positive differences (longer RAS); modeled using normal or logit-normal distributions. ΔLOS (d): Can be negative (shorter LOS with RAS); modeled as a normal distribution. Major complications (Clavien–Dindo ≥ III): Estimated on the logit scale and linked to costs when necessary.

Correlation. The covariance between Δt and ΔLOS is defined via a Gaussian copula, calibrated to prior evidence. The base case correlation coefficient (ϱ) is 0.3, with sensitivity analyses ranging from 0 to 0.5, maintaining consistent conclusions across this spectrum [13].

Procedure-Specific Notes

Rectum (primarily LAR). The ROLARR trial shows no clear superiority, whereas REAL indicates improved short-term outcomes. Japanese RWD reveal lower rates of SSI and respiratory failure and comparable overall costs, with reduced totals for LAR in one study [6–9].

Colon (right hemicolectomy and sigmoidectomy). Generally associated with longer operative times and only minor reductions in LOS, with greater reliance on Japanese data [8,9].

Stomach (DG/TG/PG). Japanese clinical studies and reviews generally report longer operative times for robotic gastrectomy, with LOS comparable to—or slightly shorter than—laparoscopy [21,22].

Duodenal local resection/PD. Limited public data available; wide priors are assigned and examined through sensitivity analyses [11–14].

3.4.3. Costs (ΔCons, Per-Minute OR Cost (c_{OR}), Per-Daybed Cost (c_{bed}), and ΔComp)

We define c_{OR} as the per-minute operating-room cost (JPY/min) and c_{bed} as the per-day inpatient bed cost (JPY/day). These terms are used in Equation (1): $\Delta CM = \Delta Rev - \Delta Cons - c_{OR} \cdot \Delta t + c_{bed} \cdot \Delta LOS - \Delta Comp$.

Consumables differential $\Delta Cons0_s$. A log-normal prior (procedure-agnostic and intentionally broad, e.g., median ¥0.5 M with a 95% range of ¥0.2–0.8 M) ensures that the required cut (%) becomes a primary outcome under significant uncertainty. This represents the current incremental per-case cost of utilizing RAS and establishes the necessary reduction for breakeven.

Per-minute OR cost c_{OR}. Based on the TDABC and OR cost literature, a triangular distribution captures inter-facility heterogeneity (e.g., minimum 1000–mode 1500–maximum 2000 JPY/min) [15,16].

Per-day inpatient bed cost c_{bed}. A triangular distribution is used (e.g., minimum 20,000–mode 30,000–maximum 40,000 JPY/day).

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Severe complication cost ΔComp. The cost of severe complications (ΔComp) may be explicitly modeled as (probability difference) × (unit cost; gamma). However, in the base case, ΔComp is set to 0 when primarily influenced by ΔLOS and is only included for procedures with confirmed significant differences [6–9,11–14].

3.4.4. Fixed Costs and Platform Sharing (F, r)

Fixed cost F. Comprises annual depreciation and maintenance derived from the price, useful life, and maintenance contracts—the mandatory annual expense of owning the platform.

Sharing rate r. Defined by the actual usage share across other departments (e.g., urology, gynecology) or by internal allocation rules. Consequently, the effective fixed cost per case is adjusted per simulation as $\frac{F_{eff}}{N}$. Therefore, higher volume dilutes the fixed cost per case only to the extent that sharing is effective; limited sharing constrains this dilution—formally encoded by these parameters.

3.5. Analysis Plan (PSA and Threshold Analyses)

3.5.1. Base Case and Scenarios

Base case. In the base case, using the distributions specified above, a 50,000-iteration Monte Carlo simulation was conducted. Outputs include the median of ΔCM_s and the distribution of Π. The means of key outputs changed by less than 1% when increasing iterations from 20,000 to 50,000, confirming convergence.

Scenarios. Mature operations feature reduced operative-time differences (Δt), facilitating decreases in ΔLOS; platform-sharing rates ranging from low to high (r = 0–80%); gradual compression of consumables differentials (ΔCons0); and the explicit inclusion of severe complication costs for selected procedures.

3.5.2. Threshold Analyses

Required-cut (%) heatmap. We present a grid with operative-time differences (Δt) on the x-axis and ΔLOS on the y-axis, plotting the necessary percentage reduction in current consumables differentials to achieve a case-level surplus, as defined by Equations (3) and (5). This heatmap highlights the extent of cost reduction required relative to achievable time and LOS improvements.

Isoprofit contours. In the r–N plane, where the horizontal axis represents platform-sharing rates (r) and the vertical axis denotes annual volume (N), we delineate Π = 0 contours. These contours illustrate the combinations of sharing rates and yearly case volumes needed to eliminate deficits based on the case-mix mean (given F_{eff} and the case-mix mean $\overline{\Delta CM}$).

No-volume-threshold map. Regions are color-coded where volume alone cannot ensure profitability, i.e., $\overline{\Delta CM} \leq 0$; specifically, areas where profitability is ≤0, indicating the absence of a feasible volume threshold (Equation (2)).

Comprehensive distributions, PSA settings, threshold-analysis formulas, and figure-reproduction scripts are provided in Appendix B (Full Disclosure of Sensitivity Analyses).

3.5.3. Sensitivity Analyses

PSA. All parameters are varied simultaneously, maintaining their correlation structure via a copula. Results are displayed as cost–revenue scatterplots and on a plane representing hospital profit [11–14].

One-way sensitivity analysis (OWSA). A tornado diagram highlights the primary drivers: ΔCons0, c_{OR}, c_{bed}, r, Δt, ΔLOS, ranked by their impact on profitability.

Scenario sensitivity. Learning-curve parameters (Equation (6)) are modified, and the explicit modeling of severe complication costs is toggled.

3.5.4. Validation

Internal validity. Consistency between manual calculations and model outputs is verified at extreme values.

External validity. The directions of major outcomes (Δt, ΔLOS, complication differences, and total cost trends) are compared with existing RCT/RWD evidence [6–9,11–14].

Transparency. The structure, assumptions, distributions, correlations, and executable code of the model are provided in Supplementary_File_S1–S3 (with figure-specific scripts in Appendix B), adhering to ISPOR–SMDM Good Research Practices for parameter estimation, uncertainty, and model transparency/validation [13,14].

Analysis environment. Implemented in Python 3.11.x (numpy, pandas, matplotlib) with fixed random seed for simulated data.

Units. Currency = JPY; time = minutes; LOS = days.

Outcomes. ΔCM_s; required cut (%); Π.

4. Results

4.1. Step 1: Decision Setting and Base-Case Parameterization

Following the six-step research workflow (Figure 1), we report the results in the same stepwise order to ensure a one-to-one correspondence between the methodology and the findings. All results are presented from the hospital perspective (index admission to 30 days) and expressed in 2025 JPY under Japan's fee schedule (1 point = ¥10). For the illustrative decision maps shown below, we use the OR cost per minute ($\boldsymbol{c}_{OR}$) and the inpatient bed cost per day ($\boldsymbol{c}_{bed}$) as the unit-cost anchors; unless otherwise specified in a scenario, the base-case examples adopt $\boldsymbol{c}_{OR}$ = 1500 JPY/min and $\boldsymbol{c}_{bed}$ = 30,000 JPY/day. The full parameter distributions, convergence checks, and supplementary outputs are provided in Appendix B.

4.2. Step 2: Target Procedures and Exogenous Revenue Differential (ΔRev)

Across the target GI procedures, the fee-schedule revenue differential (ΔRev; RAS − CLS) is procedure-dependent and treated as exogenous. In the base case, gastrectomy procedures (DG/TG/PG) benefit from positive ΔRev, whereas colon, rectum (LAR/APR), and pancreatoduodenectomy (PD) have limited to near-zero ΔRev under the current fee schedule. This heterogeneity in ΔRev constrains the achievable contribution margin and is the principal structural reason why case-level and program-level profitability differs substantially by procedure in the subsequent steps.

4.3. Step 3: Case-Level Contribution Margin Differential (ΔCM)

In the PSA (50,000 iterations), the distribution of case-level contribution margin differentials (ΔCM) by procedure was predominantly ≤0 (Figure 2). Specifically, for colon (right hemicolectomy and sigmoidectomy), rectum (LAR/APR), and PD, the negative trend prevailed because ΔRev was limited, whereas the current consumables differential (ΔCons0) and the operative-time differential (Δt) remained positive. For stomach procedures (DG/TG/PG), the deficit margin was comparatively smaller due to the increase in ΔRev; however, break-even was not attained in the base case because the current ΔCons0 exceeded the per-case allowable consumables derived from Equation (3). Credible intervals (CrI) and additional plots are available in Appendix B.

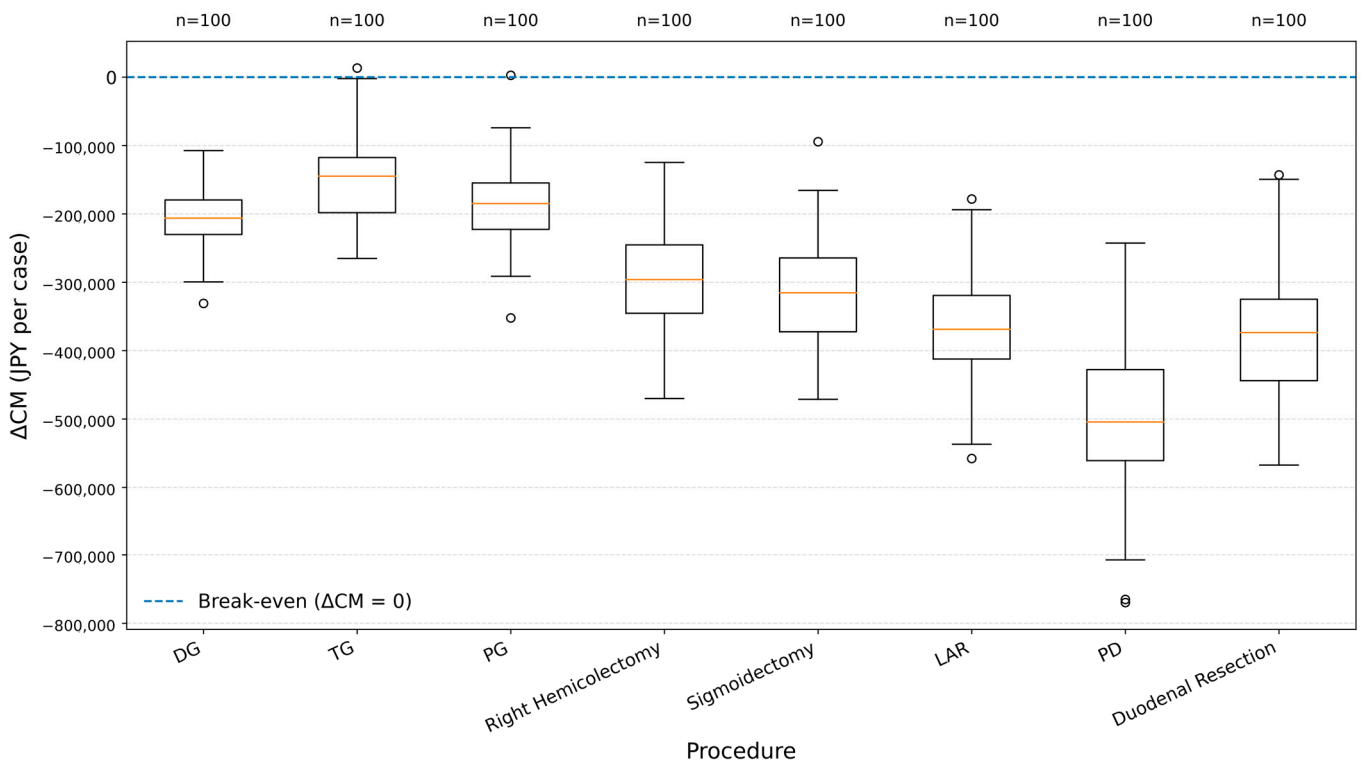

Figure 2. Distribution of case-level contribution margin (ΔCM) by procedure. Box-and-whisker plots show ΔCM (JPY per case) for each procedure (n = 100 per procedure). The orange horizon-tal line within each box indicates the median; boxes span the interquartile range (IQR); whiskers extend to the most extreme values within 1.5 × IQR; open circles denote outliers beyond the whiskers. The blue dashed horizontal line indicates the break-even point (ΔCM = 0). Standard deviations are not plotted—this is an IQR-based box plot rather than ±1σ. Abbreviations: DG, distal gastrectomy; TG, total gastrectomy; PG, proximal gastrec-tomy; LAR, low anterior resection; PD, pancreatoduode-nectomy.

4.4. Step 4: Annual Program Profit (Π) and the Existence of a Volume Threshold

Using the reference case mix in Table A4 and varying annual volume (N) while holding procedure weights (w_s) constant, the program profit distribution predominantly remained below zero across realistic annual volumes (e.g., 50–400 cases/year), indicating no "volume threshold" where merely increasing case numbers would yield profitability in the base case. This result follows the definition in Equation (2): when the case-mix-weighted mean per-case margin is ≤0, increasing annual volume (N) adds additional negative ΔCM and therefore exacerbates losses rather than approaching break-even.

4.5. Step 5: Actionable Thresholds and Decision Maps (Allowable Consumables, Required Cut, and Isoprofit)

Example (Total Gastrectomy, Base Case): ΔRev = 157,600 JPY, Δt = 30 min, ΔLOS = 1 day, c_{OR} = 1500 JPY/min, c_{bed} = 30,000 JPY/day ⇒ per-case allowable consumables upper bound = 142,600 JPY (by Equation (3)). Given the current ΔCons0 = 500,000 JPY, a reduction of 71.5% is required (by Equation (5)). (Table 1).

Table 1. Anchor-value illustration of per-case allowable consumables and required cut (%), using c_{OR} = 1500 JPY/min and c_{bed} = 30,000 JPY/day, with Δt = 30 min and ΔCons0 = 500,000 JPY/case (ΔLOS shown as 0 vs. 1 day).

Procedure	ΔRev (JPY/Case)	ΔCons$_0$ (JPY/Case)	Δt (min)	Allowable ΔCons (ΔLOS = 0)	Required Cut (ΔLOS = 0, %)	Allowable ΔCons (ΔLOS = 1)	Required Cut (ΔLOS = 1, %)
Total Gastrectomy (TG)	157,600	500,000	30	112,600	77.48	142,600	71.48
Distal Gastrectomy (DG)	94,700	500,000	30	49,700	90.06	79,700	84.06
Proximal Gastrectomy (PG)	42,700	500,000	30	−2300	100.46	27,700	94.46
Right Hemicolectomy	0	500,000	30	−45,000	109.00	−15,000	103.00
Sigmoidectomy	0	500,000	30	−45,000	109.00	−15,000	103.00
Low Anterior Resection (LAR)	0	500,000	30	−45,000	109.00	−15,000	103.00
Pancreatoduodenectomy (PD)	0	500,000	30	−45,000	109.00	−15,000	103.00
Duodenal Local Resection	0	500,000	30	−45,000	109.00	−15,000	103.00

The required cut (%) in the current consumables differential required to achieve a per-case surplus (ΔCM ≥ 0) is displayed in Figure 3 for each grid defined by the operative-time difference on the *x*-axis Δt (min; RAS − CLS, positive values indicate longer RAS time) and the LOS difference on the *y*-axis ΔLOS (days; CLS − RAS, positive values indicate shorter LOS with RAS). Moving toward the lower-right (shorter time and shorter LOS) decreases the required cut, whereas moving toward the upper-left (longer time and longer LOS) increases it. The color bar ranges from 0 to 200%, where values above 100% indicate regions that are practically infeasible at the case level. Vertical and horizontal reference lines mark Δt = 30 min and ΔLOS = 1 d. Here, $\boldsymbol{c}_{OR}$ denotes OR cost per minute and $\boldsymbol{c}_{bed}$ denotes inpatient bed cost per day.

Lever conversions: Saving each 10 OR minutes increases the allowable consumables differential by $10 \cdot \boldsymbol{c}_{OR}$ JPY, and saving each inpatient day increases it by $\boldsymbol{c}_{bed}$ JPY (e.g., $\boldsymbol{c}_{OR}$ = 1500 JPY/min ⇒ ¥15,000 per 10 min; $\boldsymbol{c}_{bed}$ = 30,000 JPY/day ⇒ ¥30,000 per day) [15,16].

By procedure type, stomach operations display a relatively broad feasible range, whereas numerous grid points for colon and rectum procedures require reductions of 50–100% or more; for PD, areas necessitating reductions exceeding 100% constitute a significant portion. Consequently, simultaneous enhancements in pricing (ΔCons0) and operational efficiencies (Δt, ΔLOS) are indispensable.

$$\text{Required cut} = 1 - \frac{\Delta Rev - c_{OR}\Delta t + c_{bed}\Delta LOS}{\Delta Cons0}$$

The *x*-axis represents the operative time difference (Δt) in minutes (RAS − CLS, positive if the RAS duration is longer), whereas the *y*-axis indicates the length of stay difference (ΔLOS) in days (CLS − RAS, positive if LOS is shorter with RAS). Vertical and horizontal reference lines at Δt = 30 min and ΔLOS = 1 day, respectively, intersect at the reference setting (×), which is annotated with the calculated required cut at that point. The color scale ranges from 0 to 200%. The parameters used for this example (TG): ΔRev = 157,600 JPY; c_{OR} = 1500 JPY/min; c_{bed} = 30,000 JPY/day; ΔCons0 = 500,000 JPY.

Additional assumptions and exact color-bar limits are provided in Appendix B.

Abbreviations: RAS, robot-assisted surgery; CLS, laparoscopic surgery; OR, operating room; Δt, operative time difference; ΔLOS, length-of-stay difference; ΔRev, revenue differential from the

fee schedule (JPY); ΔCons0, current consumables differential; c_{OR} = OR cost per minute; c_{bed} = bed-day cost.

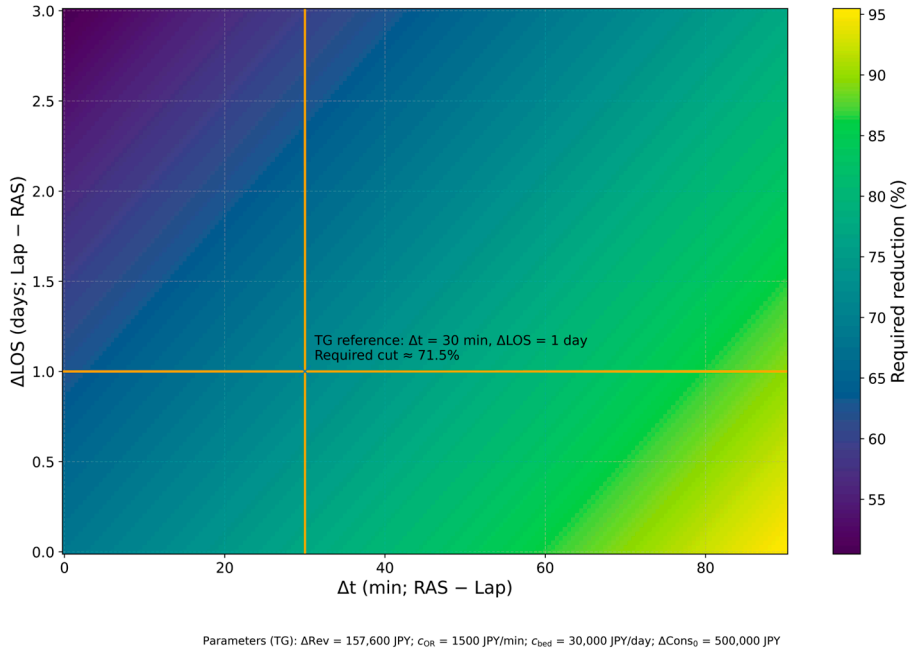

Figure 3. Required reduction (%) heatmap (example: total gastrectomy). The colors represent the necessary percentage reduction in the current consumables differential to achieve per-case breakeven, as calculated by Equations (3) and (5). The orange line indicates the per-case breakeven boundary (required reduction = 0%).

At the program level, the isoprofit contours (Π = 0) in the r–N plane are displayed in Figure 4 (horizontal axis: platform-sharing rate r; vertical axis: annual GI case volume N). Given the annual fixed cost F and the case-mix-weighted mean per-case margin, each curve displays the combinations of (r, N) that satisfy the isoprofit condition defined in Equation (2). Increasing r dilutes the effective fixed cost per case and shifts the Π = 0 contour leftward (fewer cases required to break even). When the case-mix-weighted mean per-case margin is ≤0, no feasible Π = 0 contour exists (i.e., no volume threshold). Operationally, low sharing rates hinder achieving Π ≥ 0 within feasible volumes. Expanding platform sharing, reducing ΔCons0, and enhancing the case-mix-weighted mean per-case margin enlarge the feasible (profitable) region toward the lower left (gray shading). The figure annotates F = 30,000,000 JPY/year and r = 0.5. Although platform sharing is essential for reaching the required volume, its effectiveness is limited when the case mix includes numerous procedures with minimal ΔRev. A viable path to profitability requires simultaneous improvements in pricing (consumables), operations (time, LOS), and sharing.

Each curve illustrates the relationship between the platform-sharing rate, r (x-axis), and annual GI RAS case volume, N (y-axis), where Π = 0 given the specified case mix and annual fixed cost, F. For each scenario, the break-even volume corresponds to $N(r) = \frac{(1-r)F}{\overline{\Delta CM}}$, the case-mix-weighted average per-case contribution margin differential (RAS − CLS). Increasing r shifts the contour leftward (indicating lower N). When $\overline{\Delta CM}$, no finite Π = 0 contour exists, there is no volume threshold, and additional cases exacerbate losses. The shaded area represents the profitable region (Π ≥ 0) for the base scenario. Case-mix assumptions and the Π = 0 calculations are detailed in Appendix B. (see Table A4).

Abbreviations: GI, gastrointestinal; RAS, robot-assisted surgery; CLS, laparoscopic surgery; Π, annual program profit; r, platform-sharing rate; N, annual GI RAS case volume; F, annual fixed cost; $\overline{\Delta CM}$, case-mix-weighted mean per-case contribution margin differential.

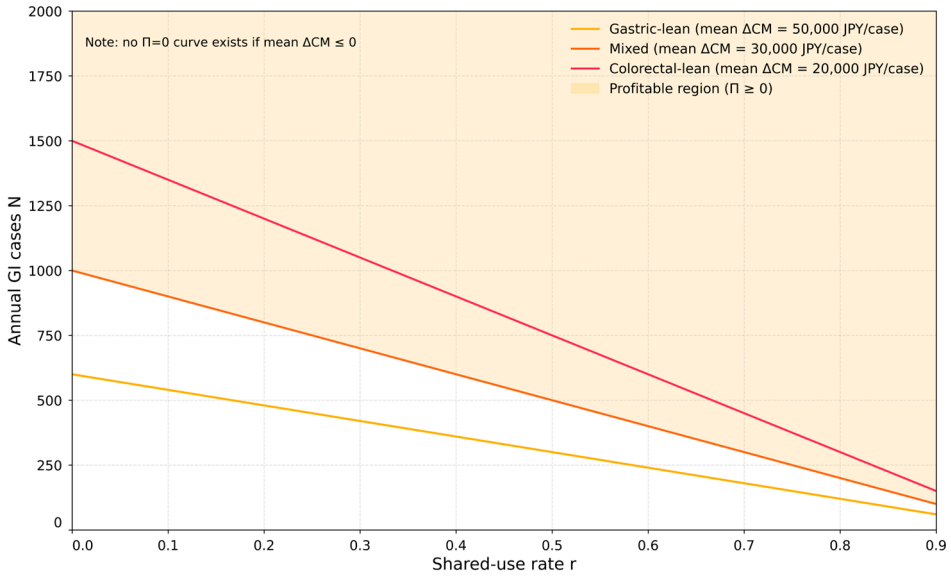

Figure 4. Isoprofit (Π = 0) contours in *r*–*N* plane.

4.6. Step 6: Uncertainty and Scenario Analyses

Under uncertainty (PSA) and scenario settings (including variations in unit costs, platform sharing, and operational performance), the decision boundaries in the required-cut and isoprofit maps shift; however, the existence of a profitability volume threshold remains governed by the sign of the case-mix-weighted mean per-case margin in Equation (2). In particular, learning-curve scenarios that reduce Δt can improve ΔCM and expand feasible regions, but procedures with near-zero ΔRev generally still require concurrent compression of ΔCons0 to reach ΔCM ≥ 0. Comprehensive PSA settings, scenario definitions, and supplementary outputs are provided in Appendix B and the Supplementary Files. The model also provides optional simultaneous-procedure and mortality-cost scenarios (Section 3.3.6) to address concomitant procedures and rare high-cost events when site-specific inputs are available.

5. Discussion

5.1. Principal Findings and Answer to the Primary Question

This study addresses a practical governance question faced by Japanese hospitals operating GI robotic platforms: can a program "grow out of" a deficit by increasing case volume under the national fee schedule? The answer from our model is conditional but clear. A profitability volume threshold exists only when the case-mix-weighted mean case-level contribution margin differential is positive; when it is non-positive, increasing annual volume increases cumulative losses rather than approaching break-even (Equation (2)). In the base case, the distribution of case-level contribution margins is predominantly ≤0 for several procedures (Figure 2), which explains why volume expansion alone does not generate profitability within realistic annual volumes.

5.2. Mechanism: Why Volume Expansion Alone Fails Under Fee-Schedule Heterogeneity

The mechanism is structural and arises from two features of the Japanese setting. First, the revenue differential (ΔRev) is procedure-dependent and externally determined by the fee schedule; gastrectomy procedures have positive ΔRev, whereas several colorectal and pancreatic procedures have limited to near-zero ΔRev. Second, the principal hospital-controlled drivers—incremental consumables (ΔCons) and incremental OR time (Δt)—remain positive in typical real-world operations. When ΔRev is small, even modest

increases in ΔCons and Δt push the case-level margin below zero, and program-level aggregation cannot reverse that sign. Therefore, "no volume threshold" is not a rhetorical claim but the direct consequence of a non-positive mean case-level margin in Equation (2). This managerial interpretation complements the broader clinical and editorial discussion of robotic rectal surgery in the literature [27,28].

5.3. Actionable Levers for Surgical Program Governance

Rather than treating profitability as a single-volume target, our outputs translate the model into operational and contracting levers. The required-cut map (Figure 3) converts time and LOS improvements into the consumable reduction required for case-level breakeven, allowing teams to set concrete negotiation targets and improvement goals. The conversion factors provide an intuitive bridge between clinical operations and finance: each 10 min reduction in OR time increases allowable consumables by $10 \cdot c_{OR}$ JPY, and each bed-day reduction increases it by c_{bed} JPY (e.g., ¥15,000 per 10 min when c_{OR} = 1500 JPY/min; ¥30,000 per day when c_{bed} = 30,000 JPY/day). The isoprofit map (Figure 4) adds the program-level lens by showing how platform sharing (r) dilutes fixed costs; however, sharing cannot compensate for a non-positive mean case-level margin. In practice, a viable path to $\Pi \geq 0$ requires coordinated action on consumables (ΔCons), OR time (Δt), LOS (ΔLOS), and sharing (r), rather than any single lever in isolation.

5.4. Additional Program Considerations: Case Mix, Simultaneous Procedures, and Mortality

Program-level results depend on case mix. To make this explicit, the model uses procedure-specific annual volumes (N_s) or equivalently case-mix weights ($w_s = N_s/N$) in computing the case-mix-weighted mean margin that determines the feasibility of $\Pi \geq 0$. Therefore, hospitals should interpret Figures 3 and 4 using their own projected procedure composition, and sensitivity analysis around case mix is essential for local decision-making.

Simultaneous (combined) procedures are an important real-world scenario. In the base case, we focus on an index GI cancer procedure to keep ΔRev and consumables accounting aligned with single K-code reimbursement. Combined procedures can materially increase consumables and OR time and may alter LOS and complication risk; consequently, they should be evaluated as scenarios by adding procedure-appropriate increments to ΔCons and Δt (and, if needed, ΔLOS and severe-complication costs) before applying the same required-cut and isoprofit framework.

Postoperative mortality was not modeled as a separate endpoint in the base case. From the hospital perspective and within a short time horizon, the cost consequences of mortality are typically mediated through resource use (intensive care unit (ICU) care, major complications, and LOS). Accordingly, we treat mortality-related costs within the severe-complication/LOS pathways and provide an optional mortality-cost scenario by incorporating an additional high-severity cost component into ΔComp. Because robust Japan-specific cost attribution for mortality is limited and institution-dependent, the mortality-cost scenario is intended to be populated with local estimates when relevant.

5.5. Limitations and Future Directions

Limitations. The main limitations are as follows.

(1) Parameter transferability: This is a model-based evaluation using inputs synthesized from trials and Japanese real-world studies. Facilities should update key parameters—especially ΔCons0, c_{OR}, c_{bed}, fixed costs, and case mix—using their own contracts and accounting.

(2) Case mix and procedure volumes: Program profit depends on procedure-specific annual volumes (N_s) and their weights (w_s). We therefore present case mix explicitly as an input (Table A4), but the study does not claim a single "national" case mix.
(3) Simultaneous procedures and coding: The base case assumes an index procedure; concomitant procedures and conversions can increase Δt and $\Delta Cons$. We address this with scenario analysis (Section 3.3.6), but robust nationwide distributions for these increments are not currently available.
(4) Mortality and rare high-cost events: Postoperative mortality is not modeled as a separate base-case endpoint because many costs are mediated through LOS and major complications. We instead provide optional high-severity cost scenarios (Section 3.3.6) that can incorporate mortality-related resource use; however, robust national estimates are scarce, and cost attribution may differ across hospitals.
(5) Scope of financial consequences: The model focuses on within-hospital contribution margins under Japan's fee schedule. Broader opportunity costs (e.g., downstream revenue, freed capacity monetization) and institutional cost-allocation rules may change the net financial impact and warrant site-specific extensions.

Future work should link the program model to multi-year capital budgeting, incorporate validated distributions for simultaneous procedures and rare events, and test external validity using multi-institutional hospital accounting data.

6. Conclusions

This study modeled GI RAS under Japan's fee-for-service regime from the hospital perspective and found that merely increasing case volume N does not ensure profitability; specifically, a volume threshold generally does not exist. The rationale is twofold: (i) the case-level contribution margin ΔCM is predominantly ≤ 0 across numerous procedures (Figure 2), and (ii) within the r–N isoprofit map, achieving $\Pi \geq 0$ is challenging at realistic volumes (Figure 4). This outcome results from the structure in Equations (1)–(4): procedure-dependent and often minimal ΔRev; residual $\Delta Cons$ and Δt; limited contribution from ΔLOS; and the fixed-cost component $(1 - r)F$.

Achieving profitability, therefore, necessitates not only maintaining volume but also simultaneously activating three additional levers alongside sharing (Figures 3 and 4):

- Price lever: Lower $\Delta Cons$ by applying the allowable upper bound and required cut (%) as defined targets (Equations (3) and (5)).
- Operations lever: Reduce Δt through OR efficiency and maintain a stable, positive ΔLOS via an Enhanced Recovery After Surgery (ERAS) [29], thereby enhancing the allowable differential per Equation (5).
- Platform lever: Increase the sharing rate r to mitigate $(1 - r)F$, effectively decreasing the subtraction term in Equation (2).

Strategies must consider procedural variations. Stomach procedures (DG/TG/PG) are closer to breakeven due to $\Delta Rev > 0$; however, they do not attain profitability if time and price remain elevated. Procedures involving the colon, rectum, and PD have $\Delta Rev = 0$; thus, only concurrent enhancements in price, time, LOS, and sharing can move the isoprofit curve into a profitable region (Figures 3 and 4).

Practical implications for GI surgical departments involve implementing the following as quarterly operational KPIs:

1. Update the procedure-specific required cut (Equation (5));
2. Prioritize actions based on the OR 10 min and LOS 1 day conversion impacts from Equation (5);
3. Coordinate sharing design and allocation with Equation (2).

From a policy standpoint, given the exogeneity of ΔRev within the national schedule, evaluation frameworks that capture clinical value and incentivize sharing can bolster hospital sustainability. Ultimately, decisions by GI surgeons and hospital leadership regarding adoption and continuation should be based not on volume projections but on the ability to achieve price × operations × sharing targets, as guided by Equations (3)–(5). For rectal cancer, more recent reports of the REAL randomized clinical trial and updated randomized-trial meta-analyses can be used to update local input parameters [30,31].

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/surgeries7010025/s1: Supplementary_File_S1 (Python script to reproduce Figure 2); Supplementary_File_S2 (Python script to reproduce Figure 3); Supplementary_File_S3 (Python script to reproduce Figure 4).

Author Contributions: Conceptualization: K.I. and N.K.; Methodology: N.K.; Software: N.K.; Formal analysis: K.I.; Validation: N.K.; Visualization: N.K.; Writing—original draft: K.I.; Writing—review and editing: N.K.; Supervision: N.K. All authors have read and agreed to the published version of the manuscript.

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Informed Consent Statement: This study used publicly available data and a model-based analysis; therefore, formal ethics committee review and informed consent were not required.

Data Availability Statement: All data used in this study are derived from publicly available sources cited in the manuscript. Parameter tables are provided in Appendix B, and reproducible scripts for Figures 2–4 are provided in Supplementary_Files_S1–S3. Additional materials are available from the corresponding author on reasonable request.

Conflicts of Interest: The authors declare no competing interests.

Abbreviations

The following abbreviations are used in this manuscript:

APR	Abdominoperineal resection
CHEERS	Consolidated Health Economic Evaluation Reporting Standards
CLS	Conventional laparoscopic surgery
CrI	Credible interval
DG	Distal gastrectomy
DPC	Diagnosis Procedure Combination
ERAS	Enhanced Recovery After Surgery
GI	Gastrointestinal
ICU	Intensive care unit
ISPOR	International Society for Pharmacoeconomics and Outcomes Research
JPY	Japanese yen
KPI	Key performance indicator
LAR	Low anterior resection
LOS	Length of stay
MDV	Medical Data Vision
OR	Operating room
OWSA	One-way sensitivity analysis
PD	Pancreatoduodenectomy
PG	Proximal gastrectomy
PSA	Probabilistic sensitivity analysis
RAS	Robot-assisted surgery
RCT	Randomized controlled trial
RWD	Real-world data

SMDM	Society for Medical Decision Making
SSI	Surgical-site infection
TDABC	Time-driven activity-based costing
TG	Total gastrectomy

Appendix A

CHEERS 2022 Checklist (Correspondence in this Manuscript)

Reference Standard: CHEERS 2022 (#12).

This manuscript adopts a cost-minimization/profit–loss model from the hospital perspective, with outcome indicators of Δt, ΔLOS, and complication differences (monetized).

Table A1. CHEERS 2022 checklist: item-by-item correspondence to this manuscript.

Item (CHEERS 2022)	Correspondence in this Manuscript (Section/Figure)	Status
Title/Abstract	Title & Abstract; study design specified	Completed
Background/Objectives	1. Background, 2. Objectives (already described)	Completed
Target Population/Subgroups	Gastrointestinal surgery (stomach, colon, rectum, duodenum, PD); procedure-specific *s*	Completed
Setting/Location	Japanese fee-for-service hospitals; hospital perspective	Completed
Perspective	Hospital perspective	Completed
Comparators	RAS vs. CLS	Completed
Time Horizon	Index hospitalization & surgery within fiscal year (capital cost on annual basis)	Completed
Discount Rate	Not applicable (within fiscal year; capital cost reported annually)	Not applicable
Health Outcomes	No QALYs (complication differences monetized)	Appropriate
Measurement of Effectiveness	Δt, ΔLOS, complication differences (Clavien–Dindo ≥ III)	Completed
Valuation of Effectiveness	Monetization (Δt, ΔLOS, c_{OR}, c_{bed}, additional costs)	Completed
Estimating Resources/Costs	ΔRev (points × ¥10), ΔCons, c_{OR}, c_{bed}, F	Completed
Currency, Price Date, Conversion	JPY; current fiscal year; point value = ¥10 explicitly stated	Completed
Choice of Model	Case-level profit–loss → program-level profit aggregation model	Completed
Assumptions	Treatment of learning curve; correlation handling; optional inclusion of complication costs	Completed
Analytical Methods	PSA, threshold analysis, isoprofit contours	Completed
Parameters	Tables A2 and A3 (Appendix B)	Completed
Incremental Costs/Outcomes	Cost differences/profit–loss differences (ΔCM, Π)	Completed
Characterizing Uncertainty	Appendix B (Full Disclosure of Sensitivity Analyses), Figures 3 and 4	Completed
Heterogeneity/Subgroups	Procedure-specific, case-mix (Figures 2–4)	Completed
Ethics/Funding/COI	Ethics approval not required (public data + model); funding/COI described	Completed
Data/Code Availability	Provided as Supplementary_Files_S1–S3 (Python scripts for reproducing Figures 2–4).	Completed

Appendix B

Model Summary

Contribution-margin differential for case *i*, procedure *s* (Equation (A1)):

$$\Delta CM_{i,s} = \Delta Rev_s - \Delta Cons_{i,s} - c_{OR}\,\Delta t_{i,s} + c_{bed}\,\Delta \mathrm{LOS}_{i,s} - \Delta \mathrm{Comp}_{i,s} \quad \text{(A1)}$$

Program-level profit (Equation (A2)):

$$\Pi = \sum_{i=1}^{N} \Delta CM_{i,s(i)} - (1-r)F = N\,\overline{\Delta CM} - (1-r)F \quad \text{(A2)}$$

Probabilistic Sensitivity Analysis (PSA)

- Objective. Evaluate the propagation of uncertainty in ΔCM and Π, and compute 95% CrI.
- Random seeds and iterations. The base-case PSA used 50,000 iterations with a fixed pseudorandom seed (42).
- Distributions (examples; replace with site-specific values).
  - $c_{\mathrm{OR}} \sim \mathrm{Gamma}(\mu = 1500,\ \mathrm{CV} = 0.25)$
  - $c_{\mathrm{bed}} \sim \mathrm{Gamma}(\mu = 30{,}000,\ \mathrm{CV} = 0.20)$
  - $\Delta\mathrm{Rev}_s$: constant based on the fee schedule (point difference × ¥10).
  - $\Delta\mathrm{Cons0}_s$: e.g., lognormal; allow lower truncation if needed.
  - $\Delta t_{i,s}$, $\Delta\mathrm{LOS}_{i,s}$: e.g., normal; do not round-off LOS to integer days.
  - Correlation. Impose rank correlation between Δt and ΔLOS (e.g., Spearman ϱ via a copula).

Outputs. Summaries for ΔCM and Π with 95% CrI; scatter/plane plots consistent with the hospital-profit framing.

Threshold Analyses

- Required reduction at the case level (%) (Equation (A3)):

$$\text{Required cut} = 1 - \frac{\Delta Cons^{\star}}{\Delta Cons0_s}, \qquad \Delta\mathrm{Cons}^{\star} = \Delta\mathrm{Rev}_s - c_{OR}\Delta t + c_{bed}\Delta\mathrm{LOS} \quad \text{(A3)}$$

- Program-level (fixed-cost adjusted) (Equation (A4)):

$$\Delta\mathrm{Cons}^{\star}_{\mathrm{program}} = \Delta\mathrm{Cons}^{\star}_{\mathrm{case}} - \frac{F_{eff}}{N} \quad \text{(A4)}$$

- Visualization. Figure 3 (Required-cut map), Figure 4 (isoprofit contours).

Learning Curve (Optional Scenario)

Apply an exponential-decay learning curve to Δt (e.g., $\Delta t(n) = \Delta t_0 \cdot n^{-k_s}$) and track year-by-year impacts on ΔCM and Π.

Reproducibility

- Code (provided as Supplementary_File_S1, figure2_cm_boxplot.py) reproduces Figure 2.
- Code (provided as Supplementary_File_S2, figure3_required_cut_heatmap.py) reproduces Figure 3.
- Code (provided as Supplementary_File_S3, figure4_isoprofit_contours.py) reproduces Figure 4.
- Environment. Python 3.11.x; numpy 1.26.x; pandas 2.2.x; matplotlib 3.8.x.

Random seed. NumPy seed fixed to 42 for simulated ΔCM in Figure 2; Figures 3 and 4 are deterministic (no randomness).

Code. The scripts in Supplementary_Files_S1–S3 are self-contained and can be executed individually to reproduce Figures 2–4.

- Inputs. Parameter table in Table A3 (Appendix B); can be loaded from CSV.

Parameter Table (Example Values + Input Template)

Device- and Hospital-Level Common Parameters

Table A2. Device- and hospital-level common parameters (example values and PSA distributions).

Symbol	Definition	Base Value (Example)	PSA Distribution (Example)	Notes
F	Annual fixed cost (depreciation + maintenance)	¥30,000,000/year	Triangular(25–40 M, mode = 30 M)	Example used in Figure 4
r	Platform-sharing rate with other departments	0.0–0.9 (range for figures)	Beta(2, 3) (optional)	$F_{eff} = (1 - r)F$
c_{OR}	OR cost per minute	¥1500/min	Gamma(μ = 1500, CV = 0.25)	Example used in Figure 3
c_{bed}	Inpatient bed cost per day	¥30,000/day	Gamma(μ = 30,000, CV = 0.20)	Example used in Figure 3

Procedure-Specific Parameter(s)

"ΔRev" is a constant from the fee-schedule point difference × ¥10 (depends on the fiscal year schedule). "$\Delta Cons0_s$" denotes the current consumables differential (based on vendor quotes/contracts). "Δt, ΔLOS" depend on site operations and surgeon experience.

Table A3. Procedure-specific parameter inputs (ΔRev, ΔCons0, Δt, ΔLOS): example values and distributions.

Procedures	ΔRev_s (JPY/Case)	$\Delta Cons0_s$ (JPY/Case)	$\mu(\Delta t_s)$ (min)	$\mu(\Delta LOS_s)$ (days)	Distribution (Example)
Total Gastrectomy (TG)	157,600	500,000	30	0~1	ΔCons0: Lognormal (GCV 0.3); Δt/ΔLOS: Normal
Distal Gastrectomy (DG)	94,700	500,000	30	0~1	Same as above
Proximal Gastrectomy (PG)	42,700	500,000	30	0~1	Same as above
Right Hemicolectomy	=0	500,000	30	0~1	Same as above
Sigmoidectomy	=0	500,000	30	0~1	Same as above
Low Anterior Resection (LAR)	=0	500,000	30	0~1	Same as above
Pancreatoduodenectomy (PD)	=0	500,000	30	0~1	Same as above
Duodenal Local Resection	=0	500,000	30	0~1	Same as above

Note: Always finalize values against the latest national fee schedule within your facility (see Refs. [4–7] in the manuscript).

Table A4. Case-mix and annual volume inputs (illustrative scenario; N = 100 cases/year).

Procedure	Annual Cases (N_s)	Case-Mix Weight ($w_s = N_s/N$)
Total Gastrectomy (TG)	10	0.10
Distal Gastrectomy (DG)	15	0.15
Proximal Gastrectomy (PG)	5	0.05
Right Hemicolectomy	15	0.15
Sigmoidectomy	20	0.20
Low Anterior Resection (LAR)	25	0.25
Pancreatoduodenectomy (PD)	5	0.05
Duodenal Local Resection	5	0.05

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