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Master Surgical Scheduling as a Complex Feedback System: A Systems Thinking and System Dynamics Perspective

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ABSTRACT

Master surgical scheduling (MSS) is a critical tactical planning problem that determines how operating room capacity is allocated to meet surgical demand. Existing research has predominantly used optimisation-based approaches focused on capacity allocation, resource utilisation, and schedule feasibility. Although these approaches provide valuable decision-support tools, they offer limited insight into the feedback mechanisms and dynamic interactions that shape long-term surgical-system performance. This study adopts a system dynamics perspective to investigate MSS as a complex feedback system. A causal loop diagram was developed through a synthesis of the literature and validated using a two-round fuzzy Delphi process involving 12 multidisciplinary experts. The diagram captures interactions among elective and emergency demand, specialty block allocation, effective capacity, downstream bed constraints, workforce conditions, treatment quality, patient satisfaction, hospital reputation, and financial resources. The analysis identifies eighteen feedback loops, comprising seven reinforcing and eleven balancing loops, organised around four cross-system mechanisms and an additional MSS-specific block-allocation and coordination mechanism; it also explicitly maps fifteen delayed effects. The findings indicate that surgical scheduling performance is shaped by the interaction between balancing mechanisms that seek to align demand and capacity and reinforcing mechanisms that intensify system pressure through patient deterioration, workforce burnout, and quality-related effects. This systems-thinking perspective highlights the importance of workforce sustainability, downstream resource constraints, treatment quality, and long-term capacity development in the design of sustainable surgical planning policies.

Keywords

Master Surgical Scheduling, System Dynamics, Systems Thinking, Hospital Operations Management, Causal Loop Diagram, Capacity Management

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1. Introduction

Within hospital surgical planning, Master Surgical Scheduling (MSS) represents a central tactical decision problem. It determines how operating room (OR) capacity is allocated over a medium-term planning horizon and how elective surgical workload is managed in the presence of emergency-related disruptions. At this level, hospital managers seek to balance surgical demand with available capacity while maintaining efficient utilisation of operating rooms and supporting infrastructure. Recent studies indicate that MSS decisions depend not only on operating room availability but also on the availability of personnel, recovery beds, and other hospital resources (Britt et al., 2021).

Operating rooms are resource-intensive and highly interdependent hospital units because surgical activity requires coordinated access to surgeons, anesthesia and nursing teams, equipment, recovery areas, intensive care, and inpatient beds. Mismatches among these resources can contribute to cancellations, delays, emergency preemption of elective capacity, overtime, and congestion (Britt et al., 2021; Naderi et al., 2021; Dodaro et al., 2022). When such pressures persist, they can also intensify staff burnout and weaken care quality (West et al., 2018; Tawfik et al., 2019). MSS is therefore important not only for efficient block allocation but also for coordinating a hospital-wide care pathway in which local decisions can create downstream operational and clinical consequences.

Most existing research on MSS and operating room planning has employed optimisation-based models to improve capacity allocation, resource utilisation, and schedule feasibility. Although these models provide valuable decision-support tools, they generally represent surgical systems through predefined resources, constraints, and planning horizons. As a result, workforce conditions, downstream resource availability, service quality, and demand evolution are typically treated as constraints, parameters, or external inputs rather than as endogenous outcomes of interacting system processes. Consequently, limited attention has been devoted to understanding how tactical MSS decisions generate longer-term effects through feedback mechanisms operating across the surgical system.

This limitation is important because surgical systems operate within a complex environment characterised by feedback processes, interdependencies, and delays. Decisions intended to improve short-term performance may alter workforce conditions, bed availability, treatment quality, and future demand patterns, thereby influencing the system's ability to deliver surgical services in the future (Naderi et al., 2021; Dodaro et al., 2022). These interactions suggest that

MSS performance cannot be fully understood through static capacity-allocation decisions alone.

Understanding such dynamics requires an approach capable of representing causal relationships, feedback effects, and time delays that influence system behaviour over extended periods. System Dynamics (SD) is particularly well-suited to this purpose because it enables analysis of how system behaviour emerges from underlying feedback structures and accumulations.

Accordingly, this study develops a causal loop diagram based on System Dynamics to examine the feedback structure underlying MSS in hospitals. The model conceptualises MSS as a dynamic feedback system in which demand, capacity, workforce conditions, downstream resources, treatment quality, organisational reputation, and financial resources continuously interact and co-evolve over time. By identifying the reinforcing and balancing feedback mechanisms embedded within this system, the study provides a systems-thinking perspective that complements existing optimisation-oriented MSS research and offers a foundation for understanding the long-term consequences of tactical surgical planning decisions.

2. Literature Review

Building on the tactical role of MSS, previous studies have primarily focused on allocating operating room time, surgical blocks, surgeons, and specialties over a medium-term planning horizon. Unlike operational scheduling, which addresses daily sequencing decisions, MSS seeks to coordinate surgical demand with available hospital resources while maintaining feasible and efficient surgical plans. Early and recent contributions have progressively expanded the scope of MSS models by incorporating multiple human and physical resources, including operating rooms, surgeons, equipment, recovery beds, and patients (Shafaei and Mozdgir, 2019; Britt et al., 2021). Additional considerations such as patient priority, surgeon availability, overtime, operating room idleness, and uncertainty in surgical duration and length of stay have further enhanced the realism of these models (Makboul et al., 2022; Kianfar and Atighehchian, 2023; Makboul et al., 2025). Collectively, this stream of research has substantially advanced the representation of resource allocation problems in surgical planning.

A related body of literature has emphasised the importance of downstream resources in determining the feasibility and performance of surgical schedules. Intensive care units, recovery units, and inpatient wards have increasingly been recognised as critical components of the surgical care pathway. To address these dependencies, researchers have incorporated

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downstream bed occupancy and resource availability into stochastic, robust, and integrated scheduling models (Santos and Marques, 2022; Heider et al., 2022; Makboul et al., 2022; Carter and Ketabi, 2024). More broadly, operating room planning studies have increasingly accounted for multiple resource constraints and operational uncertainties, including emergency arrivals, staff availability, and patient-flow variability (Naderi et al., 2021; Dodaro et al., 2022; Xue et al., 2025; Al Amin et al., 2025). These developments reflect a growing recognition that surgical performance depends on interactions between operating room resources and broader hospital operations.

Recurring specialty block allocation introduces coordination mechanisms that aggregate capacity models may obscure. Specialty block shares, inter-specialty competition, unused allocated time, emergency reserve, and ICU/recovery quotas can jointly shape the feasibility and stability of the master schedule (Heider et al., 2022; Kianfar and Atighehchian, 2023; Carter and Ketabi, 2024). The CLD therefore represents these mechanisms as endogenous tactical feedbacks rather than solely as fixed constraints.

Despite these advances, MSS research remains predominantly grounded in optimisation-based paradigms, including mathematical programming, stochastic programming, robust optimisation, and heuristic solution approaches. These methods have proven effective for capacity allocation, utilisation improvement, and schedule feasibility assessment. However, their primary objective is to identify desirable decisions within predefined planning horizons and operational constraints. Consequently, many factors that evolve through operational experience—such as workload pressure, workforce conditions, treatment quality, bed occupancy, organisational performance, and future capacity—are typically represented as parameters, constraints, or external inputs rather than as endogenous elements of the system. As MSS models have become increasingly comprehensive in representing resources and uncertainties, comparatively less attention has been devoted to understanding how these factors interact and co-evolve over time through feedback processes. This limitation is particularly important in healthcare settings, where organisational outcomes often emerge from delayed and nonlinear interactions among operational, clinical, and managerial factors. Evidence from the healthcare literature indicates that workforce burnout can affect both quality of care and organisational performance (West et al., 2018; Tawfik et al., 2019), while broader systems-oriented perspectives characterise clinician well-being as an outcome of interconnected organisational structures and processes (National Academies of Sciences, Engineering, and Medicine, 2019).

SD provides a complementary perspective for examining such interactions. Rather than focusing on decision optimisation at a specific point in time, SD investigates how feedback structures, accumulations, and delays generate system behaviour over time (Sterman, 2000; Meadows, 2008). Applications of SD in healthcare operations have demonstrated its usefulness for analysing operating room planning, operating theatre management, demand evolution, and workforce-related policies (Faeghi et al., 2023; Rahman et al., 2023). Nevertheless, the application of SD to MSS remains limited. Although existing MSS studies have increasingly incorporated a broader range of resources and operational constraints, relatively little attention has been paid to the feedback mechanisms by which elective and emergency demand, workforce conditions, bed resources, treatment quality, organisational reputation, financial resources, and effective capacity interact to shape long-term system performance. Accordingly, this study addresses this gap by developing a causal loop model of MSS that conceptualises surgical scheduling as a dynamic feedback system and examines the interactions that govern its long-term behaviour.

3. Method

This study adopts a system dynamics perspective to examine the feedback structure underlying MSS. Rather than identifying an optimal scheduling policy or developing a quantitative simulation model, the study seeks to formulate a dynamic hypothesis explaining how key operational, clinical, and managerial factors interact to influence MSS performance over time. In System Dynamics, dynamic hypotheses are commonly represented through causal loop diagrams, which provide a structured means of identifying feedback mechanisms and explaining how system behaviour emerges from underlying causal relationships (Sterman, 2000; Meadows, 2008). Accordingly, a causal loop diagram was selected as the primary modelling tool for conceptualising MSS as a dynamic feedback system.

The methodology focuses on the development of a dynamic hypothesis representing the interactions among the principal factors influencing MSS performance at the tactical planning level. The model-development process comprised five stages. First, the system boundary was defined to establish the scope of the analysis and identify the principal elements relevant to MSS. Second, key variables were identified through a synthesis of the MSS, operating room planning, healthcare operations, and workforce-management literature. Third, causal relationships among variables were established on the basis of theoretical arguments, empirical evidence reported in prior studies, and the operational logic of healthcare systems. Fourth, the proposed feedback structure was structurally validated through literature-based assessment and a two-round fuzzy Delphi process. Finally, the validated CLD was analysed to identify the reinforcing and balancing feedback loops that characterise the dynamic behaviour of the MSS system. The following subsections describe each stage of the methodology.

A focused, non-systematic search was conducted to support conceptual model development. Relevant English-language literature published up to May 2026 was identified through Scopus, Web of Science, ScienceDirect, and Google Scholar. No lower publication-year limit was imposed; recent peer-reviewed studies were prioritised, while foundational System Dynamics and fuzzy Delphi sources were retained irrespective of publication year. Search terms included "master surgical scheduling," "operating room planning," "operating room scheduling," "surgical block allocation," "emergency demand," "ICU," "recovery beds," "patient flow," "staff burnout," "treatment quality," "system dynamics," and "causal loop diagram." Backward citation searching of relevant studies was also used to identify additional sources. Sources were retained when they informed the system boundary, variables, signed causal relationships, feedback mechanisms, or delay assumptions; studies limited to patient-level sequencing or technical solution procedures without relevant system-level mechanisms were excluded.

3.1. System Boundary Definition

The system boundary was defined to capture the principal factors influencing MSS performance at the tactical planning level. Consistent with the scope of MSS, the model focuses on medium-term decisions related to operating room capacity allocation, management of elective and emergency surgical demand, and coordination of key hospital resources. Accordingly, the analysis adopts an aggregate hospital-management perspective in which variables represent system-level conditions and performance measures rather than individual entities.

The boundary includes six interrelated subsystems: demand, capacity, workforce, bed availability, quality and reputation, and financial resources. These subsystems were selected because they are frequently identified in the MSS and healthcare operations literature as important determinants of surgical performance and because they participate in endogenous feedback processes relevant to tactical decision-making. Collectively, they capture interactions among surgical demand, resource availability, workforce conditions, downstream constraints, service quality, organisational performance, and financial capacity. Together, these subsystems provide a sufficiently broad representation of the factors influencing MSS performance while maintaining a manageable level of model complexity. To strengthen MSS specificity, the boundary also represents aggregate tactical mechanisms for specialty block allocation, inter-specialty competition, emergency reserve capacity, unused allocated block time, and ICU/recovery-bed quotas.

Several elements were intentionally excluded from the model. These include individual patient characteristics, individual surgeon assignment and preference matching, same-day cancellation spillovers, detailed clinical pathways, and daily operating room sequencing activities. Although such factors influence surgical operations, they primarily affect operational-level decisions and would substantially increase model complexity without directly supporting the objective of understanding the feedback structure of MSS. The model represents specialty-level demand and ICU/recovery capacity only in aggregate tactical terms rather than as individual specialty or unit trajectories. This level of aggregation is consistent with the study's tactical focus and facilitates the identification of the dominant feedback mechanisms governing MSS behaviour.

3.2. Variable Identification and Selection

The variables included in the model were identified through a review of the MSS, operating room planning, healthcare operations, workforce management, and healthcare quality literature. The objective was not to develop an exhaustive representation of all factors that may influence surgical performance, but rather to identify the key variables required to explain the feedback mechanisms governing MSS behaviour at the tactical planning level.

Three criteria guided the variable-selection process. First, a variable had to be relevant to MSS decisions and their consequences within the hospital surgical system. Second, it had to be supported by prior literature as an important determinant of surgical performance, resource utilisation, service quality, workforce conditions, or organisational outcomes. Third, it had to participate in one or more endogenous feedback processes affecting system behaviour over time. Only variables satisfying all three criteria were retained in the model, as they contributed directly to the development of a dynamic hypothesis explaining MSS performance.

Applying these criteria resulted in the selection of variables spanning the six subsystems defined within the system boundary: demand, capacity, workforce, bed availability, quality and reputation, and financial resources. Collectively, these variables capture the principal mechanisms through which MSS decisions influence hospital performance and evolve through feedback processes. The model also includes an MSS-specific block-allocation and coordination group.

Table 1 presents the variables included in the model, organised according to the six subsystems defined within the system boundary. For each variable, the table provides a brief description, its primary conceptual foundation in the literature, and its role in the feedback structure underlying MSS performance. MSS-specific variables are listed under Block Allocation and Coordination.

Table 1. Variables included in the causal loop model

Variable Group	Variable	Description	Literature Basis	Role in Feedback Structure
Demand	Elective Demand	Demand for planned surgical services within the MSS planning horizon	MSS literature	Generates workload and contributes to unmet demand
Demand	Unmet Elective Demand	Portion of elective demand not accommodated by available capacity	MSS literature	Creates schedule pressure and future service requirements
Demand	Deterioration of Elective Patients	Worsening condition of patients due to treatment delays	Healthcare operations literature	Converts unmet demand into future emergency demand
Demand	Demand Growth Rate	Rate of change in future elective demand	Healthcare management literature	Links reputation and satisfaction to future demand dynamics
Demand	Emergency Demand	Demand for urgent surgical services requiring immediate attention	MSS and OR planning literature	Competes with elective demand for limited resources
Capacity	Emergency Surgery Rate	Rate at which emergency surgeries are performed	MSS literature	Consumes shared surgical capacity
Capacity	Elective Capacity Preemption	Reduction in elective capacity caused by emergency surgeries	MSS and OR planning literature	Transfers capacity from elective to emergency cases
Capacity	Elective Surgery Capacity	Capacity available for elective surgery after operational constraints	MSS literature	Determines ability to address elective demand
Capacity	Elective Surgery Rate	Rate at which elective surgeries are performed	MSS literature	Reduces unmet demand and waiting pressure
Capacity	Total Surgery Rate	Realised aggregate elective and emergency surgical throughput, constrained by effective capacity	Healthcare operations literature	Drives resource use, admissions, revenue, and costs while remaining capacity constrained
Capacity	Schedule Pressure	Pressure generated by imbalance between demand and capacity	OR planning literature	Influences overtime and workforce workload
Capacity	Effective Capacity	Usable surgical capacity after accounting for operational constraints	MSS and healthcare operations literature	Determines system capability to satisfy demand
Capacity	OR Utilisation	Degree to which operating room resources are used	OR planning literature	Contributes to congestion and capacity saturation

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Capacity	Capacity Saturation	Operational pressure associated with intensive resource use	Healthcare operations literature	Reduces effective capacity and quality
Workforce	Overtime	Additional work beyond regular schedules	Workforce management literature	Temporarily increases throughput but contributes to burnout
Workforce	Staff Burnout	Decline in workforce well-being and performance due to sustained workload	Healthcare workforce literature	Reduces productivity and treatment quality
Workforce	Productivity	Effectiveness of staff in delivering surgical services	Workforce management literature	Supports effective capacity and service performance
Bed Resources	Admission	Entry of surgical patients into postoperative care units	Patient-flow literature	Increases bed occupancy
Bed Resources	Occupied Beds	Postoperative inpatient, ICU, and recovery beds occupied by surgical patients	Downstream resource literature	Reduces general bed availability and the ICU/recovery quota available for block planning
Bed Resources	Bed Availability	Number of beds available for postoperative admissions	MSS and downstream resource literature	Supports surgical throughput and schedule feasibility
Bed Resources	Length of Stay	Average inpatient stay following surgery	Healthcare operations literature	Influences bed turnover and occupancy
Bed Resources	Discharge Rate	Rate at which patients leave inpatient care	Patient-flow literature	Releases occupied beds and increases availability
Quality & Reputation	Treatment Quality	Quality of care delivered to surgical patients	Healthcare quality literature	Influences outcomes, satisfaction, and recovery
Quality & Reputation	Clinical Outcome	Results of surgical treatment and recovery processes	Healthcare quality literature	Affects patient satisfaction and perceived quality
Quality & Reputation	Patient Satisfaction	Patients' perceptions of treatment quality and service experience	Healthcare quality and service management literature	Contributes to hospital reputation
Quality & Reputation	Hospital Reputation	Perceived standing of the hospital among patients and stakeholders	Healthcare management literature	Influences future elective demand
Financial Resources	Revenue	Financial income generated through surgical activities	Healthcare finance literature	Supports budget growth and resource acquisition

Financial Resources	Cost	Operational and capacity-related costs generated by surgery, overtime, and unused OR capacity	Healthcare finance literature	Reduces net budget and transmits the financial effect of OR idleness
Financial Resources	Net Budget	Financial resources remaining after revenues and costs	Healthcare management literature	Supports investment decisions
Financial Resources	Investment	Allocation of resources to capacity enhancement initiatives	Resource planning literature	Expands future effective capacity
Financial Resources	OR Idleness	Unused operating room capacity within the planning horizon	OR planning literature	Increases capacity-related cost and indicates inefficient use of allocated OR time
Block Allocation & Coordination	Specialty-Specific Elective Demand	Elective demand differentiated by surgical specialty over the MSS horizon	MSS literature	Creates specialty-level pressure on recurring block shares
Block Allocation & Coordination	Specialty Block Allocation Adequacy	Degree to which specialty block shares match demand and downstream-resource constraints	MSS and OR planning literature	Determines usable elective capacity for each planning cycle
Block Allocation & Coordination	Block Allocation Imbalance	Mismatch between specialty demand/resource needs and assigned OR block capacity	MSS literature	Generates unmet demand, competition, and reallocation pressure

Block Allocation & Coordination	Inter-Specialty Competition for OR Blocks	Competition among specialties for limited recurring OR blocks	MSS literature	Intensifies pressure to revise block allocations
Block Allocation & Coordination	Block Reallocation Pressure	Pressure to reconsider specialty block shares in response to mismatch or performance	MSS and governance logic	Drives block revision and release-policy responses
Block Allocation & Coordination	Emergency Reserve Capacity	OR time protected for expected emergency workload	MSS and OR planning literature	Limits emergency preemption of elective blocks
Block Allocation & Coordination	Available ICU/Recovery-Bed Quota	Tactical ICU and recovery capacity available to support specialty block allocations	Downstream-resource literature	Constrains specialty block-allocation adequacy
Block Allocation & Coordination	Unused Allocated Block Time	Assigned block time not used by the receiving specialty and not effectively released	OR planning literature	Increases imbalance and overall OR idleness
Block Allocation & Coordination	Master Schedule Stability	Degree to which the recurring tactical block plan remains predictable and implementable	MSS literature	Supports specialty block-utilisation performance
Block Allocation & Coordination	Frequency of Block Revisions	Frequency of evidence-based changes to specialty block assignments	MSS governance logic	Can correct mismatches but excessive revisions reduces stability

Block Allocation & Coordination	Specialty Block Utilisation Performance	Degree to which specialty-assigned blocks are effectively used	MSS literature	Reduces unused block time and strengthens effective capacity
Block Allocation & Coordination	Advance Block Release Notice Time	Advance notice provided when expected unused block time is released for reassignment	OR planning literature	Enables timely cross-specialty exchange of block capacity
Block Allocation & Coordination	Cross-Specialty Block Exchange Flexibility	Ability to transfer released OR block capacity among specialties	MSS literature	Improves utilisation of released blocks after coordination delays

3.3. Development of Causal Relationships

The causal relationships among the selected variables were developed through an iterative process that combined evidence from the MSS, operating room planning, healthcare operations, workforce management, and healthcare-quality literature with principles of SD modelling. Particular attention was given to identifying endogenous relationships through which changes in one variable influence other variables and ultimately feedback to affect the source of change. This process supported the development of a dynamic hypothesis explaining how MSS performance emerges from interactions among demand, capacity, workforce conditions, downstream resources, service quality, and financial resources.

Each causal relationship was assigned a polarity indicating the direction of influence between variables. A positive polarity denotes that the two variables move in the same direction, whereas a negative polarity denotes movement in opposite directions, all else being equal. For example, higher schedule pressure is expected to increase overtime, whereas higher staff burnout is expected to reduce workforce productivity. The polarity of each relationship was determined based on theoretical arguments, empirical findings reported in the literature, and the operational logic of hospital surgical systems, following established SD conventions.

The resulting causal structure was subsequently subjected to structural validation before being incorporated into the final CLD.

3.4. Structural Validation

The proposed causal structure underwent literature-based assessment, internal consistency review, and a structured two-round fuzzy Delphi validation. The purpose was to assess the appropriateness of the model boundary, variables, signed causal relationships, polarity assignments, delay assumptions, and feedback interpretation without changing the conceptual nature of the study.

First, the model was assessed against the MSS, operating-room planning, healthcare operations, workforce-management, and healthcare-quality literature. Second, the direction and polarity of each causal relationship were examined for internal logical consistency and redundant or ambiguous links were revised before expert evaluation.

The expert-validation stage used the Fuzzy Delphi Method, which combines iterative Delphi consensus with fuzzy representation of linguistic judgments (Murray et al., 1985; Hsu et al., 2010; Manakandan et al., 2017). The panel comprised 12 experts: nine hospital-affiliated and three university-affiliated participants with 5–15 years of relevant experience. Expertise covered OR management, surgery, anesthesiology/perioperative care, operating-theatre nursing, healthcare operations research, and System Dynamics. Experts were eligible if they held a relevant hospital or academic role and had at least five years of experience. Completion of both rounds was required for inclusion in the final consensus analysis; all 12 experts completed both rounds, so panel attrition was zero. The validation elicited professional judgments only; no patients, clinical records, clinical interventions, or identifiable personal data were involved. Participation was voluntary, and responses were coded and reported in aggregate.

Experts rated the appropriateness of each candidate variable and signed causal relationship on a five-point linguistic scale represented by triangular fuzzy numbers: very low (0, 0, 0.25), low (0, 0.25, 0.50), moderate (0.25, 0.50, 0.75), high (0.50, 0.75, 1.00), and very high (0.75, 1.00, 1.00). For each candidate item j, the aggregated fuzzy components, the distance between expert i's judgment and the group estimate, and the defuzzified score were computed as follows:

$$L_j = \frac{1}{n}\sum_{i=1}^{n} l_{ij}, \quad M_j = \frac{1}{n}\sum_{i=1}^{n} m_{ij}, \quad U_j = \frac{1}{n}\sum_{i=1}^{n} u_{ij} \tag{1}$$

$$d_{ij} = \sqrt{\frac{(l_{ij} - L_j)^2 + (m_{ij} - M_j)^2 + (u_{ij} - U_j)^2}{3}} \quad (2)$$

$$A_j = \frac{L_j + M_j + U_j}{3} \quad (3)$$

An item was retained when the expert-to-group distance did not exceed 0.20 for at least 75% of the panel and the defuzzified score was at least 0.50. Items that failed one or both criteria in Round 1 were clarified and re-evaluated in Round 2. Round 1 retained 37 of 47 variables and 49 of 71 relationships. Round 2 retained seven additional variables and 18 additional relationships; three variables and four relationships were excluded. The final CLD therefore contains 44 variables and 67 relationships. The structured validation also produced a substantive model revision. The proposed direct effect of OR idleness on revenue received 66.7% consensus in Round 2, below the predefined 75% threshold, and was excluded. Its financial implications are represented indirectly: greater OR idleness increases capacity-related costs, and higher costs reduce the net budget available for investment. Table 2 summarises the panel characteristics, decision criteria, and two-round screening outcomes.

Table 2. Summary of the two-round fuzzy Delphi validation results

Validation element	Result
Panel	12 experts: 9 hospital-affiliated and 3 university-affiliated
Expertise	OR management, surgery, anaesthesiology, OR nursing, healthcare operations research, and System Dynamics
Eligibility	Relevant hospital or academic role; at least five years’ experience; completion of both rounds required; all 12 completed both rounds
Decision rule	$d \leq 0.20$ for at least 75% of experts and $A \geq 0.50$
Variables	47 candidates; 37 retained in Round 1; 7 retained in Round 2; 3 excluded; 44 final
Relationships	71 candidates; 49 retained in Round 1; 18 retained in Round 2; 4 excluded; 67 final

3.5. The Proposed Causal Loop Diagram

Figure 1 presents the causal loop diagram developed to represent the feedback structure underlying MSS. The diagram integrates the variables and causal relationships identified through the model-development process and provides a visual representation of the dynamic hypothesis proposed in this study. Specifically, it illustrates how demand, capacity, workforce conditions, bed resources, treatment quality, hospital reputation, and financial resources interact through interconnected feedback processes that influence MSS performance over time.

The CLD serves as the foundation for identifying the reinforcing and balancing feedback loops embedded within the MSS system. By representing the causal structure linking the model variables, it facilitates the examination of how interactions among multiple feedback mechanisms generate both short-term operational outcomes and long-term system behaviour. The principal feedback loops identified within the CLD are analysed in the following section.

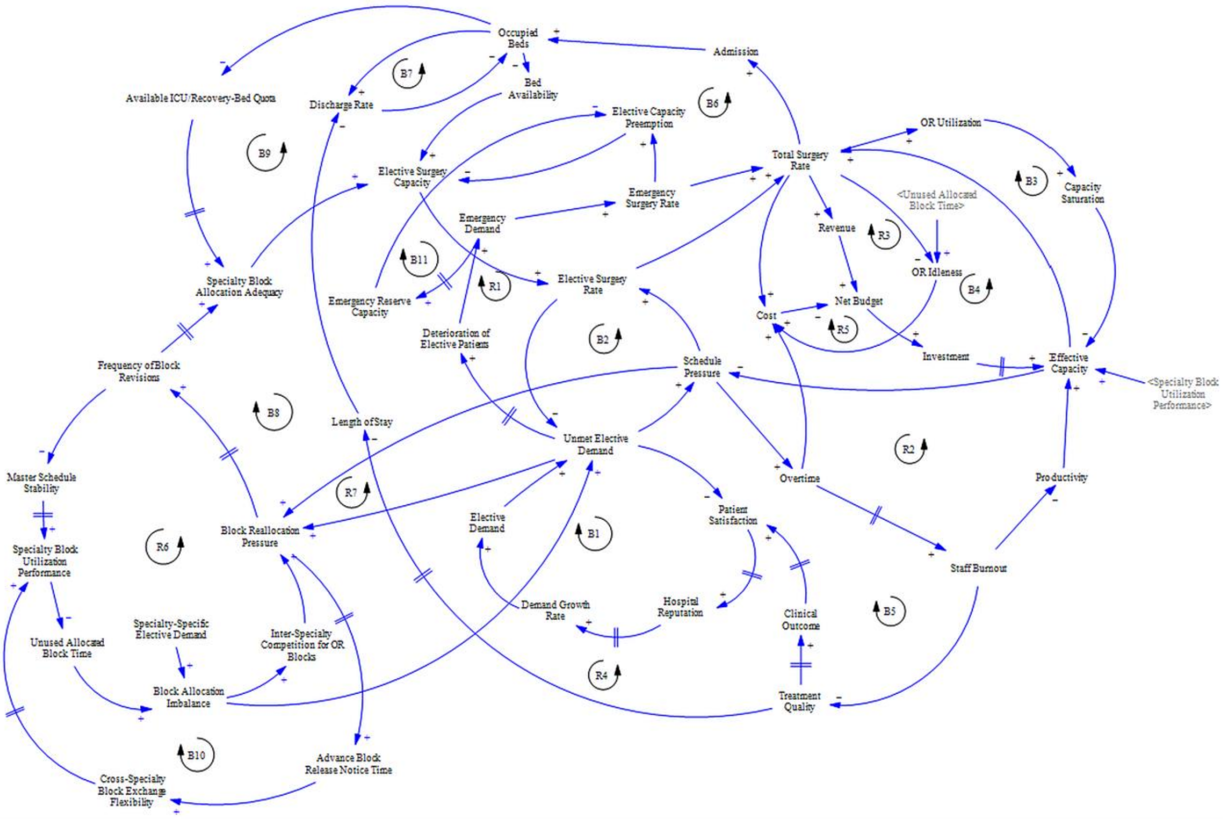

Figure 1. Final causal loop diagram of master surgical scheduling dynamics. The model comprises 44 variables and 67 signed causal relationships organised into seven reinforcing (R) and eleven balancing (B) feedback loops. Double hatch marks denote th15-causalal links with explicit time delays.

4. Results: Feedback Structure Analysis

The final CLD contains eighteen feedback loops, including seven reinforcing loops and eleven balancing loops, that collectively characterise the dynamic behaviour of the MSS system. Twelve loops represent the cross-system mechanisms, while six additional loops explicitly represent specialty block allocation, inter-specialty competition, downstream ICU/recovery constraints, block release and exchange, emergency reserve capacity, and master-schedule stability.

To facilitate analysis, the feedback structure is organised into five interrelated mechanisms: (i) demand and service dynamics, (ii) capacity and workforce dynamics, (iii) financial capacity development, (iv) bed and quality dynamics, and (v) MSS-specific block allocation and coordination. The first four mechanisms capture cross-system dynamics, whereas the fifth addresses MSS-specific tactical mechanisms related to block allocation and coordination.

4.1. Demand and Service Dynamics

The demand and service dynamics mechanism explains how the surgical system responds to imbalances between demand and available capacity. This mechanism comprises three balancing loops (B1, B2, and B5) and one reinforcing loop (R1), which collectively influence the evolution of elective demand, unmet demand, patient satisfaction, hospital reputation, and emergency demand over time.

The primary balancing mechanism is represented by loop B2. When elective demand exceeds available capacity, unmet elective demand accumulates. In response, the hospital increases the elective surgery rate, which reduces the backlog and moves the system toward equilibrium between demand and service provision. As unmet demand decreases, scheduling pressure is alleviated, thereby strengthening the loop's balancing effect.

Loop B1 introduces a demand-regulation mechanism through patient satisfaction and hospital reputation. An increase in unmet demand may reduce patient satisfaction, which in turn can weaken hospital reputation and slow future demand growth. This effect partially offsets the original increase in demand and therefore serves as a balancing mechanism. Similarly, loop B5 links treatment quality to patient satisfaction and hospital reputation. Deterioration in treatment quality may reduce patient satisfaction and weaken hospital reputation, thereby limiting future demand growth. Together, these loops connect operational performance with future demand conditions through patient perceptions and organisational reputation.

In contrast, loop R1 represents a reinforcing mechanism that can intensify demand-related pressures. As unmet elective demand increases, treatment delays may contribute to the deterioration of patients' clinical conditions. Some patients may subsequently require emergency intervention, increasing emergency demand. Because emergency cases typically receive higher priority than elective cases, rising emergency demand may increase the preemption of elective surgical capacity and reduce the capacity available for planned procedures. The resulting reduction in elective service capacity further increases unmet elective demand, thereby reinforcing the original pressure.

The interaction of these loops creates a dynamic structure in which balancing mechanisms seek to reduce unmet demand and regulate future demand growth, while the deteriorationdriven reinforcing mechanism increases emergency demand and further constrains elective capacity. Together, these feedback processes shape the evolution of demand and service performance within the MSS system.

4.2. Capacity and Workforce Dynamics

The capacity and workforce dynamics mechanism explains how efforts to increase surgical throughput influence workforce conditions and, consequently, the effective capacity of the surgical system. This mechanism consists of one reinforcing loop (R2) and one balancing loop (B3), which together govern the relationship among schedule pressure, workforce performance, capacity utilisation, and effective capacity.

Loop R2 captures the reinforcing relationship among schedule pressure, overtime, staff burnout, workforce productivity, and effective capacity. When elective demand exceeds available capacity, schedule pressure increases, and hospitals may respond by increasing overtime to accommodate additional surgical activity. In the short term, overtime increases the surgery rate and helps reduce unmet demand. However, sustained reliance on overtime may contribute to staff burnout, which reduces workforce productivity and operational performance. Lower productivity decreases effective capacity, thereby increasing schedule pressure and reinforcing the original problem.

The balancing effect within this subsystem is represented by loop B3. As surgical activity increases, operating room utilisation rises, and available resources become increasingly constrained. Higher utilisation contributes to capacity saturation, limiting the ability of the system to further increase throughput. As a result, this loop acts as a balancing mechanism that restricts growth in surgical activity as operational limits are approached.

The interaction between R2 and B3 links workforce conditions with the capacity dynamics of the surgical system. While B3 reflects operational constraints associated with resource utilisation, R2 captures the effects of workload pressure on workforce performance and effective capacity. Together, these loops describe how changes in surgical activity, utilisation, overtime, burnout, and productivity influence the evolution of system capacity over time.

4.3. Financial Capacity Development

The financial capacity development mechanism explains how operational performance influences the hospital's ability to maintain and expand surgical capacity over time. This mechanism consists of two reinforcing loops (R3 and R5) and one balancing loop (B4), which collectively govern the relationships among revenue, costs, the net budget, investment, and effective capacity.

Loop R3 represents a reinforcing capacity-development mechanism. An increase in surgical activity generates additional revenue, improving the hospital's net budget and creating opportunities for investment in surgical resources and infrastructure. These investments contribute to greater effective capacity, enabling the hospital to perform more surgical procedures and generate further revenue. Through this process, operational success can create a self-reinforcing cycle of capacity expansion.

However, capacity growth is constrained by loop B4. As surgical activity increases, operational costs also rise because of greater resource consumption, staffing requirements, and service-delivery expenses. Higher costs reduce the net budget available for investment, thereby limiting future capacity expansion. This balancing mechanism reflects the financial constraints associated with increasing surgical throughput and counteracts the growth process represented by R3.

A second reinforcing mechanism is represented by loop R5, which captures the financial consequences of unused operating-room capacity. Higher surgical throughput reduces OR idleness; lower idleness, in turn, reduces capacity-related cost and improves the net budget available for investment. Increased investment expands effective capacity and supports additional surgical throughput. Conversely, persistent idleness raises the cost of unused capacity, weakens the net budget, and constrains subsequent capacity development. During the second Fuzzy Delphi round, the proposed direct effect of OR idleness on revenue did not reach the predefined consensus threshold and was therefore excluded, a decision consistent with the dependence of revenue effects on hospital reimbursement arrangements. Accordingly, R5 represents the financial consequences of idle capacity through operating cost and the net budget rather than through a direct revenue channel.

The interaction among these loops links operational performance, financial outcomes, and capacity development. While R3 describes a reinforcing process through which successful operations support future capacity expansion, B4 introduces financial constraints associated with rising costs. At the same time, R5 captures the effects of resource underutilisation on financial performance and future investment. Together, these feedback mechanisms shape the evolution of capacity through the interaction of surgical activity, financial resources, and investment decisions.

4.4. Bed and Quality Dynamics

The bed-and-quality dynamics mechanism explains how downstream resources influence surgical capacity and how operational pressure affects treatment quality and future system performance. This mechanism consists of two balancing loops (B6 and B7) and one reinforcing loop (R4), which collectively capture the interactions among bed occupancy, treatment quality, workforce conditions, and surgical throughput.

Loop B6 represents the balancing effect of bed availability on surgical capacity. As the total surgery rate increases, more patients are admitted to postoperative care units, increasing bed occupancy and reducing bed availability. Lower bed availability constrains elective surgery capacity, limiting the number of additional procedures that can be scheduled. This mechanism acts as a downstream capacity constraint that regulates surgical throughput and limits further growth in surgical activity.

Loop B7 captures the balancing relationship between bed occupancy and patient discharge. As bed occupancy increases, discharge activity releases beds and improves bed availability. Increased bed availability supports surgical capacity and reduces pressure on downstream resources. Through this process, the loop contributes to system stability by facilitating patient flow through the hospital.

In contrast, loop R4 represents a reinforcing mechanism linking treatment quality, patient recovery, bed utilisation, workforce conditions, and capacity performance. A decline in treatment quality may lead to poorer clinical outcomes and longer lengths of stay, increasing bed occupancy and reducing bed availability. Reduced bed availability constrains surgical capacity, increases schedule pressure, and contributes to greater reliance on overtime. Sustained overtime may increase staff burnout and reduce workforce productivity, which can further impair treatment quality. Through this process, quality deterioration can propagate throughout the surgical system and reinforce the original problem.

The interaction among these loops links downstream bed resources with surgical capacity, workforce conditions, and treatment quality. While B6 and B7 regulate patient flow and bed availability, R4 captures the reinforcing effects through which changes in treatment quality influence bed utilisation, operational pressure, and workforce performance. Together, these feedback mechanisms describe how downstream resources and quality-related factors shape the evolution of MSS performance over time.

4.5. MSS-Specific Block Allocation and Coordination

The MSS-specific block-allocation and coordination mechanism explains how specialty demand, block assignment, downstream capacity, and managerial adaptation jointly shape the stability and effective use of the master schedule. It comprises four balancing loops (B8-B11) and two reinforcing loops (R6 and R7). The balancing loops represent corrective responses that improve allocation, recover unused capacity, protect elective blocks, and align surgical activity with downstream resources; the reinforcing loops capture conditions under which competition and repeated revision can destabilise the schedule.

Loop B8 represents the balancing correction of block-allocation mismatch. As unmet elective demand rises, pressure to reconsider specialty block shares increases. Evidence-based revisions improve the adequacy of block allocation and expand usable elective capacity, allowing more elective procedures to be completed and reducing unmet demand. The loop therefore describes a managerial correction process through which persistent backlog prompts adjustment of the master schedule.

In contrast, loop R6 captures a reinforcing specialty-competition and instability trap. A mismatch between specialty demand and assigned block capacity increases competition for recurring operating-room time and intensifies pressure for reallocation. Repeated revisions reduce master-schedule stability and weaken specialty block-utilisation performance, leaving more allocated time unused. The resulting unused capacity aggravates the original allocation imbalance and sustains the cycle.

Loop B9 represents the balancing influence of downstream ICU and recovery capacity on specialty block allocation. Higher surgical activity increases postoperative admissions and bed occupancy, reducing the ICU/recovery-bed quota available to support additional elective blocks. The resulting constraint lowers block-allocation adequacy and elective capacity, moderating subsequent surgical activity. This loop makes the feasibility of MSS explicitly dependent on downstream resources rather than operating-room availability alone.

Loop B10 captures the corrective effect of early block release and cross-specialty exchange. When allocated time remains unused, allocation imbalance and reallocation pressure increase. Management may respond by requiring earlier release notice and facilitating transfer of released time across specialties. Greater exchange flexibility improves block-utilisation performance and reduces unused allocated time, thereby counteracting the initial imbalance.

Loop R7 represents a reinforcing capacity-pressure-revision instability mechanism. A decline in effective capacity increases schedule pressure and prompts more frequent block reallocation.

Although revision is intended to restore alignment, repeated changes can reduce schedule stability, weaken block-utilisation performance, and further diminish effective capacity. The loop therefore highlights how excessive corrective activity may become self-defeating when revisions outpace the system's ability to adapt.

Loop B11 describes an emergency reserve buffer. Sustained emergency demand encourages the hospital to protect a larger share of operating-room capacity for urgent cases in subsequent planning cycles. Adequate reserve capacity reduces the extent to which emergency activity preempts elective blocks, thereby preserving elective capacity, supporting elective throughput, and limiting the accumulation of unmet elective demand. As the elective backlog and subsequent deterioration pressure decline, future emergency demand is moderated.

Together, these loops show that MSS performance depends not only on the nominal amount of operating-room time assigned to each specialty but also on the stability, adaptability, and downstream feasibility of the block plan. Corrective governance can improve allocation and recover unused time, whereas persistent competition and excessive revision can erode schedule stability and effective capacity. The combined structure therefore clarifies why block-allocation policies must be coordinated with emergency protection, downstream bed capacity, and timely cross-specialty exchange. Table 3 summarises the functional role and core causal mechanism of the six MSS-specific feedback loops.

Table 3. MSS-specific feedback loops incorporated into the final causal loop diagram

Loop	Name	Core mechanism
B8	Block Reallocation Correction	Backlog-driven revision improves specialty block-allocation adequacy and elective capacity.
R6	Specialty Competition and Instability Trap	Allocation imbalance intensifies competition and repeated revision, weakening schedule stability and block utilisation.
B9	ICU/Recovery-Constrained Specialty Allocation	Postoperative occupancy limits the ICU/recovery quota available to support feasible specialty blocks.
B10	Early Block Release and Recovery	Early release and cross-specialty exchange recover block time that would otherwise remain unused.
R7	Capacity–Pressure–Revision Instability	Capacity loss increases revision pressure, while repeated change further weakens schedule stability and effective capacity.
B11	Emergency Reserve Buffer	Adaptive emergency reserve limits the recurrent preemption of elective block capacity.

4.6. Explicit Representation of Time Delays

Fifteen delayed causal effects are explicitly marked by double hatch marks in Figure 1. These delays represent clinical deterioration, workforce fatigue, outcome realisation, reputation formation, investment implementation, downstream-capacity adjustment, and administrative adaptation of the master schedule. Explicitly mapping the delays is important because corrective actions may appear ineffective or may be continued after underlying conditions have already begun to change, creating overshoot, policy resistance, or schedule instability. Table 4 identifies each delayed relationship and its dynamic interpretation.

Table 4. Explicit time delays represented in the final causal loop diagram

Delay	Delayed relationship	Dynamic interpretation
D1	Unmet Elective Demand → Deterioration of Elective Patients	Clinical deterioration develops after prolonged waiting.
D2	Overtime → Staff Burnout	Burnout accumulates after sustained workload.
D3	Treatment Quality → Clinical Outcome	Clinical outcomes become observable after care.
D4	Treatment Quality → Length of Stay	Quality-related recovery effects influence stay after a lag.
D5	Clinical Outcome → Patient Satisfaction	Patients evaluate outcomes after treatment and recovery.
D6	Patient Satisfaction → Hospital Reputation	Reputation changes gradually through accumulated experience.
D7	Hospital Reputation → Demand Growth Rate	Referral and choice behaviours respond with a delay.
D8	Investment → Effective Capacity	Capacity investment requires implementation time.
D9	Block Reallocation Pressure → Frequency of Block Revisions	Administrative review precedes schedule revision.
D10	Frequency of Block Revisions → Specialty Block Allocation Adequacy	Revised block shares affect later planning cycles.
D11	Master Schedule Stability → Specialty Block Utilisation Performance	Utilisation adapts after the schedule stabilizes.
D12	Available ICU/Recovery-Bed Quota → Specialty Block Allocation Adequacy	Downstream capacity is incorporated into subsequent block decisions.
D13	Block Reallocation Pressure → Advance Block Release Notice Time	Release-policy requirements are adjusted after managerial review.

D14	Cross-Specialty Block Exchange Flexibility → Specialty Block Utilisation Performance	Coordination benefits appear after reassignment.
D15	Emergency Demand → Emergency Reserve Capacity	Reserve capacity adapts across planning cycles.

5. Discussion and Policy Implications

The feedback structure developed in this study suggests that MSS should be viewed as a dynamic capacity-management problem rather than solely as a tactical scheduling or capacity-allocation problem. Although existing MSS research has generated valuable insights into operating room allocation, resource utilisation, and schedule feasibility, the proposed model indicates that MSS performance emerges from the interaction of multiple operational, clinical, organisational, and financial processes. Consequently, the long-term behaviour of surgical systems cannot be fully understood by examining operating room capacity in isolation.

A central insight of the study is that MSS performance is shaped by the continuous interaction between stabilising and amplifying feedback processes. The balancing mechanisms identified in the model seek to align demand and capacity by reducing unmet demand, regulating demand growth, and managing downstream resource utilisation. However, these mechanisms operate alongside reinforcing processes that can intensify system pressure over time. Persistent delays in elective care may increase future emergency demand through patient deterioration, sustained overtime may erode effective capacity through workforce burnout, and declining treatment quality may increase bed occupancy and further constrain surgical throughput. These findings suggest that short-term operational improvements do not necessarily translate into long-term system improvement, particularly when they activate reinforcing processes that gradually undermine capacity and performance.

The model further highlights that effective capacity should not be regarded as a fixed resource determined solely by operating rooms, staffing levels, or bed availability. Rather, capacity emerges endogenously from the interaction among workforce conditions, treatment quality, downstream resources, financial investments, and operational pressure. From this perspective, capacity is not merely allocated through MSS decisions but continuously shaped by the consequences of previous decisions. This observation helps explain why hospitals may experience persistent capacity shortages even when substantial efforts are made to increase throughput and resource utilisation.

The study also emphasises the interconnected nature of surgical-system performance. The proposed feedback structure demonstrates that variables often examined separately in the MSS literature—including unmet demand, emergency demand, workforce burnout, treatment quality, bed availability, financial resources, and hospital reputation—are linked through multiple feedback pathways. As a result, changes originating in one part of the system may propagate throughout other subsystems and generate delayed consequences that are difficult to identify using static or narrowly defined analytical perspectives. Understanding MSS therefore requires attention not only to immediate scheduling outcomes but also to the broader feedback structure within which those outcomes occur.

From a theoretical perspective, this study contributes to the MSS literature in several ways. First, it introduces a feedback-based perspective that complements the dominant optimisation-oriented view of MSS. Whereas optimisation models typically focus on identifying desirable decisions within predefined planning horizons and operational constraints, the proposed CLD highlights the endogenous mechanisms through which MSS decisions influence future system conditions. Second, the model integrates operational, clinical, workforce, financial, and reputational factors within a unified conceptual framework. Third, it identifies the reinforcing and balancing feedback processes through which these factors interact to shape MSS performance over time. Collectively, these contributions extend the conceptualization of MSS from a resource-allocation problem to a dynamic system characterised by feedback, delays, and adaptation.

The findings also have important managerial implications. First, hospital managers should recognise that increasing surgical throughput alone may not constitute a sustainable response to capacity shortages. Policies that rely heavily on overtime and workforce intensification may reduce waiting lists in the short term but can simultaneously increase burnout and weaken effective capacity over time. Second, efforts to maximise operating room utilisation should be coordinated with the availability of downstream resources, particularly postoperative bed capacity, because constraints outside the operating room may ultimately limit system performance. Third, the model suggests that indicators such as workforce well-being, treatment quality, patient satisfaction, bed occupancy, and emergency-demand growth should be monitored alongside traditional operational metrics such as throughput and utilisation. Finally, the financial feedback structure highlights the importance of aligning short-term operational decisions with long-term investment strategies that strengthen organisational adaptability and support sustainable capacity development.

The MSS-specific loops add a further managerial implication: block governance should be evaluated jointly with specialty demand and downstream ICU/recovery capacity. Frequent reactive revisions may correct a local imbalance but can also reduce schedule stability and block-utilisation performance. Earlier release of expected unused blocks, flexible cross-specialty exchange, and an explicitly planned emergency reserve can reduce unused time and repeated elective preemption without relying solely on additional physical capacity.

6. Limitations and Suggestions

Several limitations should be acknowledged. First, the proposed model is conceptual and represented through a causal loop diagram; therefore, it does not provide quantitative estimates of system behaviour or policy effectiveness. Second, the analysis focuses on tactical-level MSS dynamics. Specialty block allocation and downstream ICU/recovery constraints are represented in aggregate form, while individual patient trajectories, surgeon assignment, and daily case sequencing remain outside the boundary. Third, the causal structure was validated through a two-round Fuzzy Delphi process, but it has not been calibrated or behaviourally tested using longitudinal hospital data. Future research could develop a quantitative stock-and-flow model, estimate parameters using hospital data, and evaluate policies related to block release, emergency reserve, workforce support, downstream capacity, and long-term investment.

Finally, hospital governance, financing, and decision rights vary across settings, particularly between public and private hospitals. Accordingly, variables such as net budget, investment, block reallocation, and cross-specialty exchange may not be directly controllable or operationalized identically in every institution. Although the panel included hospital-based OR managers and clinical leaders, the study did not include an in-depth, hospital-specific managerial interview or case calibration. Future applications should therefore adapt variable definitions and causal links through local managerial interviews and longitudinal data before policy testing.

7. Conclusion

This study developed a System Dynamics-based causal loop diagram to investigate MSS as a dynamic feedback system. Following a two-round Fuzzy Delphi validation with 12 multidisciplinary experts, the final model contains 44 variables, 67 signed causal relationships, seven reinforcing loops, eleven balancing loops, and fifteen explicitly mapped time delays. The model integrates cross-system mechanisms linking demand, capacity, workforce, beds, quality, finance, and reputation with six MSS-specific loops that represent specialty block allocation, inter-specialty competition, ICU/recovery constraints, block release and exchange, schedule stability, and emergency reserve capacity.

The study contributes to the MSS literature by introducing a feedback-based perspective that complements existing optimisation-oriented approaches. Whereas most MSS research focuses on resource allocation and schedule feasibility within predefined planning horizons, the proposed model highlights the endogenous processes through which scheduling decisions influence future system conditions. By integrating operational, clinical, workforce, financial, and reputational factors within a unified framework, the study provides a broader understanding of the mechanisms that shape long-term surgical-system performance.

Overall, the findings suggest that MSS should not be viewed solely as a tactical scheduling problem but as a dynamic capacity-management challenge embedded within a complex hospital system. Effective and sustainable surgical planning requires attention not only to throughput and resource utilisation but also to specialty block governance, schedule stability, emergency reserve, workforce sustainability, treatment quality, downstream resource availability, and long-term capacity development. The proposed CLD provides a focused foundation for future quantitative System Dynamics modelling and policy evaluation.

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