

# Cost Leakage Points in Hospital Supply Chain and Control Methods: A Comprehensive Literature Review

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**Abstract:** *The hospital supply chain represents a significant portion of healthcare operational expenditures, yet it is notoriously plagued by systemic inefficiencies and hidden cost leakage. Cost leakage points—such as expired inventory, off-contract purchasing, phantom stocks, and inter-departmental hoarding—drain critical financial resources that could otherwise be allocated to patient care. This comprehensive literature review examines the theoretical and practical underpinnings of cost leakage within medical supply networks and proposes the integration of advanced control systems to mitigate these financial losses. By synthesizing principles from robust data-driven iterative control, synthetic causal inference, and game-theoretic multi-agent modelling, this paper bridges the gap between industrial systems engineering and healthcare administration. The findings suggest that adopting continuous, mathematically rigorous control frameworks can dynamically suppress supply chain disturbances, optimize inventory routing, and secure data infrastructures against malicious interference. Ultimately, this review provides a strategic roadmap for modernizing hospital supply chain management through advanced algorithmic interventions.*

**Keywords:** Hospital supply chain, Cost leakage, Procurement inefficiency, ABC-VED analysis, Digital twin technology, Kaizen

## 1. Introduction and Scope of Hospital Supply Chain Cost Leakage

Hospital supply chains represent one of the most complex and resource-intensive operational systems in healthcare, yet they remain vulnerable to significant financial losses through various cost leakage mechanisms. Cost leakage refers to unplanned, unaccounted, or preventable expenses that dissipate throughout the supply chain without adding value to clinical care or patient outcomes. Healthcare systems globally lose substantial revenues annually due to inefficiencies in procurement, inventory management, distribution, and monitoring processes [1]. The magnitude of these losses varies considerably across hospital types and regions, with studies indicating that hospitals can recover 15-50% of annual consumable costs through systematic supply chain optimization.

The healthcare supply chain encompasses multiple interconnected nodes, from pharmaceutical manufacturers and medical device suppliers through central distribution centers to end-user clinical departments. Unlike industrial supply chains, hospital supply chains must simultaneously optimize for patient safety, regulatory compliance, clinical effectiveness, and financial sustainability—a balancing act that often results in overcautious stocking practices and substantial waste [2]. Recent research demonstrates that inefficient inventory management alone accounts for 7-19% cost overruns compared to optimal practices, with expiration and shrinkage representing the largest single contributors to leakage. Understanding these cost leakage points and implementing evidence-based control methods has become strategically essential as healthcare organizations face mounting financial pressures and budget constraints.

## 2. Identification of Major Cost Leakage Points

### 2.1 Expiration and Product Wastage

Product expiration represents the most significant source of quantifiable cost leakage in hospital supply chains, accounting for 28-35% of total inventory losses in many institutions. Blood component wastage alone demonstrates this challenge, with studies from tertiary hospitals reporting wastage rates of 13-19% before implementing targeted interventions [5]. The primary causes of expiration-related losses include inaccurate demand forecasting, overstocking behaviour driven by fear of stockouts, poor inventory rotation practices, and inadequate storage temperature control for perishable items [2].

Maintenance inhalers exemplify this problem across respiratory care units, where emergency stockpiling in ward locations leads to predictable expiration without clinical use [7]. When these items were removed from bedside storage, institutions eliminated wastage while simultaneously reducing carbon emissions equivalent to driving across entire countries. Pharmaceutical installations demonstrate similar patterns, with expiration losses increasing dramatically during supply disruptions or pandemic situations, when inventory classification systems must be dynamically adjusted to reflect clinical priorities [8].

### 2.2 Inventory Shrinkage and Unaccounted Loss

Inventory shrinkage—the difference between recorded and actual inventory—represents a hidden but substantial cost leakage point that receives insufficient attention in healthcare operations. This category encompasses multiple loss mechanisms: genuine errors in stock-keeping unit (SKU) tracking, damaged goods during storage and handling, pilferage (both deliberate and inadvertent), and data entry inaccuracies that corrupt inventory systems [9]. Research from hospitals implementing barcode tracking systems

reveals shrinkage rates of 3-8%, with high-value items showing disproportionately higher loss percentages [10].

The complexity of hospital inventory- thousands of SKUs, multiple storage locations, frequent bin transfers, and multiple user access points- creates substantial opportunities for untracked losses that accumulate silently. Traditional visual estimation and manual counting methods compound this problem, with studies showing that hospitals relying on manual inventory practices report 10-15% accuracy discrepancies compared to automated systems [3]. The impact extends beyond direct financial loss; shrinkage-driven uncertainty increases safety stock levels, further inflating inventory holding costs and exacerbating the expiration problem.

### 2.3 Procurement and Purchasing Inefficiency

Procurement inefficiency represents a systemic cost leakage point rooted in complex purchasing processes, supplier consolidation failures, and suboptimal negotiating practices. Hospitals often maintain relationships with excessive numbers of suppliers for similar product categories, foregoing volume discounts and favourable pricing power [12]. The fragmentation of purchasing decisions across clinical departments- where purchasing authority remains decentralized to accommodate clinical preferences- eliminates enterprise-wide negotiating leverage and perpetuates higher-than-necessary unit costs.

Evidence demonstrates that hospitals utilizing strategic procurement practices, such as sole-source or preferred-supplier arrangements combined with competitive bidding cycles, achieve 20-30% cost reductions for medical supplies [13]. Conversely, ad-hoc purchasing driven by emergency restocking needs forces procurement at premium prices. The bullwhip effect, wherein upstream suppliers receive distorted demand signals from inconsistent hospital ordering patterns, generates overproduction and forces suppliers to accept suboptimal margins that are passed downstream as higher prices or reduced service quality.

### 2.4 Overstocking and Excess Inventory Holding Costs

Overstocking represents a dual cost leakage mechanism: not only are capital resources immobilized in excess inventory, but the holding costs (including storage, handling, temperature control, and staff time) accumulate without generating clinical value. Hospitals frequently maintain safety stock levels far beyond mathematically optimal quantities, driven by uncertainty regarding demand patterns, supplier reliability, and lead times [14]. For perishable items and items with shelf-life constraints, this conservative approach escalates exponentially- extended holding times reduce product shelf-life remaining, increasing expiration risk and necessitating price reductions at donation or disposal.

The financial impact is substantial: a 200-bed hospital maintaining 40-50 days of inventory supply instead of mathematically optimal 25-30 days can experience holding cost penalties exceeding \$500,000 annually. This burden falls disproportionately on capital-intensive items such as blood products, vaccines, and specialty pharmaceuticals. The

pandemic period illustrated this phenomenon starkly, as hospitals competing for scarce supplies built excess inventory that later expired, creating windfall losses of millions of dollars across healthcare systems [8].

### 2.5 Inadequate Tracking and Information System Deficiencies

The absence of real-time tracking systems and fragmented information architectures creates endemic visibility gaps that prevent timely identification and correction of supply chain disruptions. Many hospitals continue relying on legacy systems that provide only periodic inventory snapshots rather than continuous visibility, delaying response to emerging stockout or overstock situations [15]. When procurement, inventory management, storage, and clinical departments operate with disconnected information systems, data inconsistencies accumulate, generating unreliable insights for decision-making [6].

Information asymmetry between hospital administrators and clinical departments—where clinicians withhold or misrepresent inventory needs to protect departmental autonomy—perpetuates inefficient purchasing. Without transparent, real-time visibility into consumption patterns, procurement planners' resort to conservative forecasting assumptions. Studies demonstrate that implementation of integrated information systems can improve inventory accuracy from 75% to 95%, reduce procurement lead times by 30%, and enable demand-driven rather than push-based procurement models [2].

### 2.6 Storage, Handling, and Distribution Losses

Physical product loss during storage and distribution represents a frequently underestimated cost leakage point. Inadequate storage facilities with poor temperature control, insufficient humidity management, or compromised security contribute to product degradation and theft. Research on anaesthetic drug supply chains in resource-constrained settings reveals that 55-90% of hospitals report inefficient storage conditions causing significant wastage [16]. Handling losses accumulate through multiple mechanisms: spillage during transfer, contamination from improper handling, package damage, and environmental exposure.

Transportation-related losses include spoilage from temperature excursions (particularly for cold-chain items like vaccines and blood products), mechanical damage, theft in transit, and delays that consume shelf-life without generating clinical value [17]. A comprehensive analysis of transport optimization for medical waste demonstrates that suboptimal routing increases costs by 7-14% and augments contamination risks, necessitating remediation expenditures [18]. The supply chain externalities- energy consumption, emissions, and environmental impact—represent hidden costs that hospitals increasingly recognize as financial liabilities under carbon accounting frameworks.

### 3. Inventory Classification and Prioritization Frameworks

#### 3.1 ABC-VED Analysis: The Gold Standard Classification System

The ABC-VED (Always-Better-Control / Vital-Essential-Desirable) analysis represents the foundational inventory classification methodology in hospital supply chain management, enabling stratified control intensity aligned with financial and clinical importance [19]. The ABC component classifies items based on consumption value: Category A items (approximately 10-20% of SKUs) represent 60-80% of expenditure and require continuous monitoring; Category B items (20-30% of SKUs) account for 15-30% of expenditure and require periodic review; Category C items (50-70% of SKUs) represent only 5-10% of expenditure and permit automated reordering.

The VED component simultaneously classifies based on clinical criticality: Vital items are essential for patient survival and cannot be substituted, Essential items can be replaced if unavailable, and Desirable items enhance patient care but lack immediate criticality [20]. The integrated ABC-VED matrix generates nine strata, with items classified as AV (high-spend, vital) receiving the strictest monitoring, while CD items (low-spend, desirable) permit greater operational latitude. Implementation across multiple tertiary hospitals demonstrates consistent cost reductions of 15-20%, accompanied by improved inventory accuracy and reduced stockouts [21].

#### 3.2 FSN Analysis and Demand Pattern Classification

FSN (Fast-moving, Slow-moving, Non-moving) analysis complements ABC-VED classification by stratifying items based on consumption velocity. Fast-moving items (typically 30-40% of SKUs) represent continuous revenue and require lean inventory approaches to minimize holding costs. Slow-moving items (40-50% of SKUs) consume minimal stock and often represent specialty drugs or low-frequency procedures; these benefit from just-in-time approaches that reduce capital commitment while maintaining availability. Non-moving items (10-20% of SKUs) represent inventory that has not been consumed within defined periods and frequently represent dead stock or superseded products that accumulate obsolescence costs.

Hospitals integrating FSN analysis into procurement strategies achieve 25-35% improvements in inventory turnover and reduce dead-stock accumulation by 40-60% [22]. The combined ABC-VED-FSN framework enables hospitals to apply differentiated control strategies: A-Fast items utilize Kanban systems with minimal safety stock; A-Slow items employ periodic-review reordering with higher safety stocks; C-items utilize automated reordering with minimal manual oversight [23].

#### 3.3 Multi-Criteria Classification and Advanced Segmentation

Advanced classification methodologies extend beyond two-dimensional ABC-VED analysis to incorporate multiple

decision criteria simultaneously. Multi-criteria approaches integrate procurement difficulty (SDE: Scarce, Difficult, Easy), product lifecycle stage, seasonal variation, supplier reliability metrics, and clinical substitutability into comprehensive segmentation models [24]. These sophisticated frameworks recognize that cost implications vary dramatically based on multidimensional characteristics: a high-cost, non-critical item with reliable supply requires different management than a low-cost, vital item with volatile supply.

Research demonstrates that hospitals implementing AHP-TOPSIS (Analytic Hierarchy Process-Technique for Order of Preference by Similarity to Ideal Solution) or MUSIC-3D classification achieve inventory optimization improvements of 40-45%, with particular effectiveness in managing spare parts and specialized equipment [22]. Machine learning extensions of these frameworks enable dynamic classification adjustments as consumption patterns evolve, demand seasonality shifts, or supply chains experience disruptions, improving response agility and reducing forecast errors by 20-30%.

### 4. Inventory Control Techniques and Methodological Implementation

#### 4.1 Just-in-Time (JIT) Inventory Systems

Just-in-Time inventory management—originating from Toyota manufacturing and adapted for healthcare—aims to receive items at the precise moment clinical use requires them, eliminating intermediate storage and associated costs [14][25]. Hospital implementations of JIT reduce inventory holding by 30-50%, minimize expiration losses, and free substantial capital for other operational priorities. However, JIT success in healthcare requires fundamentally different preconditions than manufacturing: reliable, consistent demand forecasts; responsive suppliers capable of rapid delivery cycles; robust quality assurance; and coordinated logistics.

Successfully implementing JIT for high-consumption items (gauze, syringes, routine pharmaceuticals) generates immediate cost savings and improved turnover, while non-critical applications to low-demand specialty items risk stockouts and clinical disruptions [25]. Hospitals combining JIT for fast-moving items with safety-stock reserves for unpredictable-demand or critical items achieve optimal balance, reducing total supply costs by 25-35% while maintaining clinical availability above 99%.

#### 4.2 Modified Kanban Systems for Healthcare

Kanban systems- employing visual signals and predetermined bin quantities to trigger replenishment- have proven highly effective in hospital environments where staff require simple, intuitive mechanisms for inventory management without sophisticated technology. The three-year case study at a Middle Eastern inpatient unit demonstrated dramatic success: weekly consumable costs declined 40-50% (from 8,500to8,500 to 8,500to4,300), out-of-stock rates fell from 0.04 to near-zero per 1,000 inpatient days, and staff compliance improved from 76% to 95%.

Kanban effectiveness derives from its simplicity and visual nature: physical bin locations with color-coded quantity markers communicate inventory status at a glance, reducing ordering delays and human decision variability. The modified Kanban approach—incorporating replenishment triggers, bin systems, standardized Kanban boards, and consumption-based quantity settings—addresses healthcare-specific challenges of variable demand and multiple clinical priorities [3]. Staff satisfaction increases substantially because Kanban eliminates the cognitive burden of inventory estimation, empowering clinical workers to focus on patient care while automatically maintaining appropriate supply levels.

#### 4.3 ABC Analysis-Based Selective Control Policies

Selective control policies recognize that different items require fundamentally different management approaches based on financial and clinical importance. The three-bin or two-bin system for Category C items uses automatic reordering triggered by visual quantity depletion, minimizing administrative overhead. Category B items employ periodic review with targeted service levels (typically 90-95% availability), while Category A items receive continuous monitoring with sophisticated forecasting and safety-stock optimization [24].

Advanced selective policies incorporate Economic Order Quantity (EOQ) calculations to minimize the sum of ordering and holding costs for each category. However, healthcare applications must recognize that perfect EOQ optimization often conflicts with clinical preferences (preferring frequent deliveries of small quantities to minimize storage space) and supplier capabilities [20]. Integrated ABC-selective control approaches allow hospitals to optimize Category A items precisely while accepting simpler heuristics for lower-value items, generating cost benefits while maintaining implementation feasibility.

#### 4.4 Value Stream Mapping and Lean Process Optimization

Value stream mapping (VSM)—a Lean methodology for visualizing workflow and identifying non-value-added activities—has demonstrated remarkable effectiveness in identifying cost leakage points and process bottlenecks in hospital pharmacy and supply operations [21]. By mapping the complete drug disbursement process from warehouse order to clinical unit delivery, hospitals identified opportunities to reduce total process time from 1,925 to 435 minutes (77% reduction), with value-added time comprising only 20.5% of the total [23].

VSM implementation reveals that many activities consuming staff time and resources—waiting for inventory counts, searching for misplaced items, resolving data discrepancies, managing substitutions—represent non-value-added or necessary-but-not-value-added activities. Process redesign guided by VSM insights enables simultaneous improvement across multiple dimensions: labor efficiency, inventory accuracy, delivery timeliness, and waste reduction. Combined with Lean Six Sigma methodologies, VSM-guided improvements generate 35-45% cost reductions through systematic elimination of process waste [23].

## 5. Technology and Digital Solutions for Cost Control

### 5.1 Real-Time Tracking Systems: RFID and IoT Integration

Radio Frequency Identification (RFID) and Internet of Things (IoT) technologies enable unprecedented real-time visibility into supply chain movements, transforming inventory management from periodic snapshots to continuous streams of actionable data [10]. RFID tags on inventory items transmit location and identification data as items move through warehouses, transport vehicles, and clinical units, enabling automated data capture without manual scanning or data entry. IoT sensors augment this capability by monitoring environmental conditions (temperature, humidity, vibration), triggering alerts when conditions deviate from safe parameters.

The performance improvements from RFID-IoT integration are substantial: supply chain disruption prediction improves to 65%, temperature variation prediction reaches 80%, and automated verification time decreases by 30% compared to manual processes [10]. Real-time visibility enables hospitals to identify and correct inventory discrepancies immediately rather than discovering them during periodic physical counts, reducing shrinkage from 6-8% to 2-3%. Combined with dashboard visualization systems, RFID-IoT infrastructure empowers procurement and operations teams to make proactive decisions based on current supply status rather than assumptions about inventory levels.

### 5.2 Blockchain and Distributed Ledger Systems

Blockchain technology—enabling decentralized, immutable record-keeping of supply chain transactions—has emerged as a transformative solution for ensuring supply chain transparency, preventing counterfeiting, and maintaining data integrity. Each transaction in a blockchain-based system generates a permanent, cryptographically verified record that cannot be altered retrospectively, creating an auditable trail accessible to all authorized stakeholders. Smart contracts automate routine transactions, automatically triggering replenishment, quality verification, and payment settlement based on predefined conditions [11].

Hospital implementations of blockchain in pharmaceutical supply chains demonstrate exceptional effectiveness: end-to-end traceability accuracy reaches 98.5%, counterfeit medicine detection improves by 35%, and product recalls decrease by 30% [10]. The transparency benefits extend beyond internal operations to stakeholder communication; patients, regulators, and insurers can verify product authenticity and supply chain handling throughout the medication journey from manufacture through patient consumption. Cost savings from reduced fraud, improved recall efficiency, and eliminated intermediaries typically justify implementation costs within 18-24 months.

### 5.3 Artificial Intelligence and Predictive Analytics

Artificial Intelligence (AI) and machine learning algorithms have revolutionized demand forecasting, enabling hospitals to

predict consumption patterns with substantially higher accuracy than traditional time-series methods. Enhanced LSTM models with attention mechanisms reduce root mean square error (RMSE) by 18.8%, significantly improving forecast accuracy for both fast-moving and slow-moving items. Anomaly detection algorithms identify unusual consumption patterns suggesting potential quality issues, clinical practice changes, or supply chain disruptions, enabling rapid investigation and correction.

AI-driven applications extend beyond forecasting to resource optimization: machine learning identifies optimal inventory levels for each item category considering demand uncertainty, supply lead time variability, holding costs, and stockout penalties. Inventory turnover improves by 26.5%, transportation costs decline by 18.2%, and hospitals achieve balanced availability across all categories. Predictive maintenance algorithms applied to medical equipment identify failure risks before equipment breakdown, reducing downtime by 28.5% and preventing cascade disruptions [20].

#### 5.4 Integrated Enterprise Resource Planning (ERP) and Automation

Comprehensive ERP systems integrating procurement, inventory, logistics, financial, and clinical functions create the information infrastructure necessary for cost control at scale. Automated dispensing cabinets in clinical units connected to central inventory systems provide real-time stock visibility and prevent expired medications from being dispensed. Robotic dispensing systems reduce medication selection errors by 95%, prevent expired product use, and improve efficiency by 40-50% compared to manual pharmacy operations.

Electronic systems integration addresses the information asymmetry problems that plague manual processes: inventory managers possess current consumption data in real time, enabling optimized procurement rather than conservative padding. However, successful ERP implementation requires substantial organizational change management, staff training, and integration with legacy systems that many hospitals continue operating. Hospitals that treat ERP implementation as comprehensive process redesign rather than simple system substitution achieve the greatest cost and operational benefits [6].

## 6. Digital Twin and Advanced Simulation Technologies

### 6.1 Digital Twin Applications in Supply Chain Optimization

Digital twin technology- creating virtual replicas of physical supply chain systems that simulate real-world operations—has emerged as a powerful tool for testing optimization scenarios without operational disruption. A digital twin of a hospital supply chain enables simulation of demand fluctuations, supply disruptions, and alternative operational policies, providing evidence-based guidance for process changes that would otherwise be attempted through trial-and-error approaches.

Performance improvements from digital twin-guided optimization are remarkable: process optimization yields 15-25% reduction in production cycles, energy consumption and downtime decrease 15-20%, productivity improves up to 25%, and overall cost savings reach 30% [21]. Digital twins enable hospitals to simulate impact of new clinical programs on supply chain demand, anticipate bottlenecks before they manifest operationally, and test alternative layouts for storage facilities before capital investment. The flexibility and responsiveness improvements enhance hospitals' ability to adapt rapidly to demand changes, new disease patterns, or supply disruptions.

### 6.2 Machine Learning for Intelligent Inventory Optimization

Machine learning algorithms, trained on historical consumption patterns, supplier performance metrics, and external variables (seasonal patterns, pandemic effects, regulatory changes), enable dynamic optimization of inventory parameters. Unlike static EOQ or safety stock calculations that remain unchanged until manual revision, machine learning models continuously adapt to emerging patterns, improving forecast accuracy and reducing both stockouts and overstocking simultaneously [17].

Natural language processing applied to clinical documentation and procurement communications enables extraction of demand signals from unstructured data, improving forecast accuracy by 15-25% compared to relying solely on historical consumption. Reinforcement learning techniques enable algorithms to identify optimal ordering and allocation decisions through trial-and-error learning, discovering unconventional but effective solutions that human planners might overlook [7].

## 7. Process Improvement Methodologies and Operational Excellence

### 7.1 Lean and Six Sigma in Healthcare Supply Chains

Lean and Six Sigma methodologies, originating in manufacturing but successfully adapted to healthcare, target systematic elimination of waste and reduction of process variation. The DMAIC (Define, Measure, Analyze, Improve, Control) framework guides hospitals through structured improvement cycles: clearly defining the problem and improvement objectives, establishing baseline metrics, analyzing root causes of inefficiency, implementing targeted solutions, and implementing controls to sustain improvements. Studies of Lean Six Sigma implementation in pharmaceutical inventory management reveal waste reduction of 30-40%, decreased stockouts by 35-50%, and improved procurement efficiency by 25-35% [23].

The "five R's" framework (Reduce, Rearrange, Re-engineer, Reorder, Remove) systematizes lean thinking in hospital contexts: reducing unnecessary inventory holdings, rearranging storage locations for improved efficiency, re-engineering processes to eliminate non-value-added steps, reordering workflows to improve flow, and removing obsolete items and practices. These methodologies generate sustained improvements because they address root causes

rather than symptoms, creating organizational cultures of continuous improvement that persist long after formal improvement projects conclude.

## 7.2 Kaizen and Continuous Improvement Culture

Kaizen- the Japanese philosophy of continuous incremental improvement—has proven particularly effective in healthcare supply chain contexts where major disruptions are infeasible but accumulated small improvements generate substantial results. Unlike one-time reengineering projects that risk unintended consequences, Kaizen engages front-line staff in identifying and implementing improvements in their work areas, generating both operational benefits and enhanced staff engagement [3].

Hospital implementations of Kaizen in supply chain operations have generated cumulative improvements of 40-60% over 3-5-year periods [26]. Staff satisfaction increases substantially because employees recognize their contributions to operational success and experience growing autonomy as processes become more efficient. The sustainability of Kaizen-driven improvements exceeds project-based improvements because the cultural change persists even as external improvement initiatives conclude.

## 7.3 Total Quality Management (TQM) and Quality Control Standards

Total Quality Management frameworks emphasize that quality is not a separate concern but must be integrated throughout operations, from supplier selection through inventory storage to clinical delivery [4]. Hospitals implementing comprehensive TQM approaches establish quality standards for suppliers, implement in-process quality checks, and maintain records of product quality performance. These practices prevent quality-driven costs from masking in unexplained waste or hidden losses.

The Scan4Safety program in NHS hospitals illustrates TQM in practice, using barcoding technology and data standards to track medical products and identify quality issues. Standardized identification of patient, product, procedure, and location enables rapid identification of quality problems: batches with above-average defect rates trigger enhanced scrutiny, and root cause analysis identifies manufacturing or handling issues. These proactive quality management approaches prevent recalls, reduce liability exposure, and maintain customer trust more effectively than reactive quality assurance [9].

## 8. Procurement Strategy and Supplier Management

### 8.1 Strategic Sourcing and Vendor Consolidation

Strategic procurement approaches—consolidating supplier relationships, negotiating volume discounts, and implementing preferred vendor programs- generate substantial cost savings through increased leverage [12]. Rather than distributing purchasing across numerous suppliers of similar products, strategic sourcing concentrates volume with selected vendors in exchange for favourable

pricing, guaranteed availability, and vendor-managed inventory arrangements. Case studies demonstrate that conversion to sole-source suppliers for haemostatic products achieved 25% cost reductions without clinical quality compromises [13].

Vendor-managed inventory programs represent a sophisticated form of strategic sourcing where suppliers assume responsibility for maintaining appropriate inventory levels at hospital locations, with compensation based on consumption rather than purchase orders. This arrangement aligns supplier and hospital incentives toward optimal availability with minimal inventory holding, reducing both stockouts and overstocking simultaneously. The success of these arrangements depends on robust data sharing, strong relationship governance, and clear performance metrics.

### 8.2 Supplier Relationship Management and Performance Metrics

Supplier relationship management extends beyond transactional purchasing to encompass collaborative planning, performance monitoring, and continuous improvement. Hospitals implementing sophisticated supplier scorecards tracking on-time delivery, quality metrics, pricing accuracy, and responsiveness to expedited requests create accountability frameworks that drive supplier performance improvements [24]. Regular supplier reviews, collaborative problem-solving when performance lapses occur, and recognition programs for high-performing suppliers create positive engagement that benefits both parties.

Research demonstrates that hospitals investing in supplier relationships achieve more favourable pricing, enhanced availability during supply disruptions, and innovative offerings supporting process improvements. Conversely, purely transactional relationships focused on extracting lowest prices often result in diminished service quality, reduced willingness to accommodate urgent requests, and missed opportunities for collaborative improvement.

### 8.3 Purchasing Compliance and Ethical Sourcing

Purchasing compliance programs- ensuring procurement decisions follow established procedures, vendor selection criteria, and pricing parameters- prevent unauthorized purchases that circumvent cost controls. Documentation requirements, approval workflows, and exception reporting enable organizations to identify and correct deviations from established procurement practices [4]. Multi-level authorization requirements prevent individual clinicians or purchasers from making high-cost commitments without institutional oversight.

Ethical sourcing considerations—ensuring vendors meet environmental standards, lab practices, and social responsibility criteria- increasingly influence procurement decisions. These considerations add cost in some categories but generate long-term value through risk mitigation, brand reputation protection, and alignment with organizational values. The integration of sustainability into procurement strategy represents a paradigm shift from pure cost

minimization toward total-cost-of-ownership approaches that account for environmental and social impacts [12].

## 9. Financial Accountability and Control Mechanisms

### 9.1 Cost Allocation and Activity-Based Accounting

Activity-based costing (ABC)—allocating expenses to clinical activities, departments, or patient populations based on actual resource consumption—provides far superior decision-making information compared to traditional departmental cost allocation. Rather than averaging costs across all patients, ABC identifies that certain procedures or patient populations consume disproportionate resources, enabling targeted improvements and pricing decisions. Pathological examination cost analysis using process-based accounting revealed that specific test types consumed dramatically different amounts of consumables, enabling targeted cost reduction [6].

Implementation of process management information systems tracking consumable consumption by activity enabled a tertiary hospital to reduce overstock inventory from 996,527 Chinese Yuan to 832,402 (16.5% reduction), reduce glass slide waste from 17,244 to 1,538 (91% reduction), and improve diagnostic timeliness from 65.07% to 95.46%. These improvements stemmed from visibility into actual resource consumption patterns previously obscured in aggregated cost data [6].

### 9.2 Budget Management and Cost Control Frameworks

Effective hospital budget management requires monthly reconciliation of actual versus planned expenditures, investigation of significant variances, and rapid corrective action when variances suggest emerging problems. Game-theoretic combined weighting methods—integrating both subjective expert judgment and objective data analysis—provide more balanced cost control evaluation than single-perspective approaches. A tertiary hospital implementing this framework reduced 12.9% budget overruns to minimal variances, with greatest improvements in areas where cost control indicator weights were meaningfully increased.

Cost control optimization schemes must address system-wide performance rather than optimizing individual expense categories at the cost of overall performance. Reducing drug costs through aggressive generics substitution, for example, might increase labour costs if more staff time is required for administration or management of adverse effects [14]. Comprehensive cost frameworks account for these interdependencies and identify truly optimal strategies that minimize total cost while maintaining clinical quality.

### 9.3 Performance Monitoring and Key Performance Indicators

Comprehensive supply chain performance monitoring requires tracking metrics across multiple dimensions: financial (cost per unit, procurement costs), operational (inventory turnover, stockout rates, delivery reliability), clinical (medication error rates, patient safety events), and

quality (defect rates, customer satisfaction) [13]. Excessive focus on any single metric risks creating perverse incentives; minimizing inventory holding costs might increase stockout frequency and clinical risks, while maximizing availability might inflate holding costs excessively.

Balanced scorecards showing relationships between multiple metrics help organizations understand these trade-offs and identify truly optimal performance levels [13]. Key performance indicators should include leading indicators (predictive of future problems) and lagging indicators (reflecting past performance), enabling proactive response to emerging issues rather than waiting for problems to fully manifest. Monthly or quarterly performance reviews with clinical, administrative, and financial leadership ensure that supply chain performance remains aligned with organizational priorities.

## 10. Implementation Challenges and Sustainability Strategies

The implementation of supply chain optimization initiatives in hospitals is frequently constrained by a range of organizational, technical, and financial challenges. Resistance to change among healthcare staff remains a primary barrier, often driven by limited awareness of the benefits of new systems and disruption to established workflows (Kotter, 1996; Burnes, 2004) (28). In parallel, inadequate technical infrastructure and poor system integration hinder the effective deployment of digital tools such as enterprise resource planning (ERP), radio-frequency identification (RFID), and Internet of Things (IoT) technologies, resulting in fragmented data environments and limited visibility (Kache & Seuring, 2017). Financial constraints further restrict adoption, particularly in resource-limited settings, where high upfront costs for technology acquisition, training, and process redesign may not be immediately feasible (de Vries & Huijsman, 2011). Data quality issues, including inaccurate inventory records and lack of real-time tracking, exacerbate inefficiencies and contribute to persistent cost leakage (Papalex et al., 2020). Additionally, skill gaps among supply chain personnel and insufficient training programs limit the effective utilization of advanced analytical tools (Govindan et al., 2015). Fragmented procurement systems and overreliance on a limited supplier base further reduce operational efficiency and increase vulnerability to supply disruptions, while complex regulatory and compliance requirements add layers of administrative burden (WHO, 2017) (29).

To address these challenges, hospitals must adopt integrated and sustainable strategies that align technological innovation with organizational transformation. A phased implementation approach, beginning with pilot projects in high-impact areas, allows institutions to manage risk and demonstrate value before scaling interventions (Rogers, 2003). Effective change management, supported by strong leadership commitment and stakeholder engagement, is critical to overcoming resistance and ensuring long-term adoption (Kotter, 1996) (32). Investment in digital transformation— including the integration of ERP systems with RFID, IoT, and artificial intelligence (AI)-driven analytics— can significantly enhance real-time visibility, demand forecasting, and inventory optimization (Kache & Seuring, 2017; Ivanov et al., 2019).

Strengthening data governance through standardized processes and continuous monitoring improves decision-making accuracy and operational transparency (Papalexi et al., 2020) (30). Capacity building through regular training and the development of specialized supply chain roles is essential for sustaining performance improvements (Govindan et al., 2015). Furthermore, centralized procurement and standardized vendor management practices enable cost savings through economies of scale and improved negotiation power, while supplier diversification enhances resilience against disruptions (de Vries & Huijsman, 2011). The integration of lean and environmentally sustainable practices, such as Just-in-Time (JIT) inventory and waste reduction initiatives, supports both economic and ecological objectives (Womack & Jones, 2003). Finally, the establishment of robust governance frameworks, supported by clearly defined key performance indicators (KPIs) and continuous audit mechanisms, ensures accountability and alignment with regulatory standards, thereby embedding sustainability into hospital supply chain operations (WHO, 2017) (32).

### 10.1 Organizational Change Management and Staff Engagement

Successfully implementing supply chain control methods requires managing organizational change, addressing staff resistance, and building commitment to new processes and technologies [15]. Staff scepticism about new systems stems from legitimate concerns: concerns about job security when automation reduces manual work, preferences for familiar work patterns, and concerns about technology reliability. Effective change management addresses these concerns through transparent communication, inclusive process design that incorporates staff input, training programs ensuring competence with new systems, and recognition of contributions to successful transitions.

The Kanban case study demonstrated that explicit attention to staff satisfaction alongside operational improvements generated 79% to 90% satisfaction improvement, compared to projects where staff experienced the changes as imposed requirements. Staff empowerment- enabling frontline workers to identify problems and propose solutions rather than simply implementing prescribed changes- builds commitment and generates superior solutions that technical experts might overlook.

### 10.2 Data Quality and System Integration Challenges

Successful supply chain optimization depends on high-quality data: accurate inventory records, reliable consumption forecasts, complete supplier performance data, and consistent information flows [24]. Many hospitals inherited data quality challenges from legacy systems characterized by inconsistent coding, duplicate records, missing information, and unreliable transactions. Addressing these challenges requires parallel system operation during transition periods, extensive data cleaning and validation, and mechanisms for identifying and correcting errors that inevitably emerge during system implementation.

System integration challenges emerge when existing procurement, inventory, logistics, financial, and clinical

systems operate with incompatible data formats, differing system architectures, or competing information priorities [15]. Modern API-based integration approaches enable data sharing between systems while preserving their specialized functionality, but require investment in integration platforms and governance frameworks defining data ownership and quality standards.

### 10.3 Sustainability and Long-Term Maintenance

Supply chain improvements prove sustainable only when supported by ongoing management commitment, regular performance review, and continuous refinement of processes and parameters. Cost reductions achieved through initial implementation projects tend to gradually erode as priorities shift, staff turnover introduces less-experienced personnel, and organizations revert to prior practices [18]. Sustainability requires embedding improvements into standard operating procedures, incorporating improvement metrics into performance evaluations, and maintaining executive visibility into supply chain performance.

Long-term sustainability also requires periodic reassessment of optimization parameters: safety stock levels established during implementation may become excessive as demand patterns stabilize and forecasting improves; supplier performance metrics may require adjustment as supply relationships evolve; technology platforms require upgrades to maintain security and remain compatible with evolving information systems. Hospitals maintaining Kaizen cultures, where frontline staff continuously identify incremental improvements, achieve superior long-term performance compared to organizations dependent on periodic formal improvement projects [8].

## 11. Discussion

### Practical Implications and Deployment Considerations

Deploying advanced control methodologies within a hospital's supply chain requires careful alignment with existing operational infrastructure. Practically, the integration of iterative data-driven controllers must interface seamlessly with the hospital's current Enterprise Resource Planning (ERP) systems. This transition shifts the burden of inventory management from frontline clinical staff to automated, centralized algorithms, allowing nurses and doctors to focus entirely on patient care rather than tracking missing supplies. However, successful deployment necessitates rigorous staff training to ensure accurate primary data entry at the point of care, as the efficacy of any data-driven control method is intrinsically tied to the fidelity of its inputs. Furthermore, management must establish clear protocols for overriding algorithmic decisions during unprecedented black-swan events that exceed the theoretical bounds of the modeled disturbances.

## 12. Limitations and Failure Modes

Despite the theoretical robustness of the proposed framework, several critical limitations and potential failure modes must be acknowledged.

- Non-Stationary Demand Bounds: The assumption that demand disturbances are strictly bounded may fail during

catastrophic global events (such as a severe pandemic), rendering the historical datasets incompatible with the new reality and causing the iterative controller to calculate dangerously low safety stocks.

- **Data Sparsity in Smaller Networks:** Rural or underfunded hospitals may lack the digital infrastructure necessary to generate the high-frequency datasets required for advanced discrete-time control methods, forcing them to rely on dangerously sparse data that degrades controller accuracy.
- **Computational Overhead:** Implementing advanced causal inference techniques, particularly geodesic synthetic control methods for complex functional data (Kurusu et al., 2025), introduces significant computational overhead that may exceed the processing capabilities of standard hospital IT departments.

### 13. Ethical Considerations and Risks

The application of strict algorithmic efficiency to healthcare logistics introduces profound ethical considerations that differ fundamentally from standard industrial control environments.

- **Risk of Over-Optimization:** Aggressively minimizing cost leakage and eliminating redundant inventory can lead to a state of over-optimization, where a minor disruption in the supply chain results in life-threatening stockouts of critical care items. The ethical mandate of a hospital is patient preservation, which must always supersede supply chain leanness.
- **Data Privacy and Integration:** Advanced forecasting often requires correlating supply usage with patient admission data, diagnosis codes, and treatment plans. This deep integration raises significant ethical risks regarding patient privacy and the potential exposure of Protected Health Information (PHI) if the supply chain databases are compromised or inadequately anonymized.

### 14. Future Work

The continuous evolution of both medical logistics and control theory provides fertile ground for future research expansions.

**Exploration of Quantum Optimization:** As supply chains become increasingly global and complex, future work should investigate the application of quantum control methods to solve massive, non-convex logistics optimization problems. Techniques utilized for robust entanglement in multi-level quantum systems (Valahu et al., 2022) (Randall et al., 2017) and quantum Lyapunov control for system convergence (Cong & Meng, 2013) could eventually be abstracted to manage the exponentially growing variables in global medical procurement.

**Dynamic Game-Theoretic Budgeting:** Future research should deeply integrate dynamic game theory models (Wang et al., 2020) to create intelligent incentive structures. By modelling hospital departments as autonomous agents within a cooperative game, administrators could design automated budgetary rewards that natively discourage hoarding and rogue purchasing, fundamentally aligning individual departmental goals with holistic hospital financial health.

### 15. Conclusion

- 1) Cost leakage is a major but often unmeasured threat to hospital financial sustainability.
- 2) Effective supply chain optimization can recover **20–50% of expenditures** by identifying and controlling leakage points.
- 3) Key sources of cost leakage include:
  - Expiration and wastage
  - Inventory shrinkage
  - Procurement inefficiencies
  - Overstocking
  - Poor tracking systems
  - Handling and storage losses
- 4) These leakages are **preventable**, not unavoidable, and can be reduced using evidence-based control methods.
- 5) Advanced inventory classification techniques improve control and prioritization:
  - ABC–VED analysis
  - FSN analysis
  - Multi-criteria classification frameworks
- 6) These methods help categorize large volumes of SKUs and enable **targeted management based on financial and clinical importance**.
- 7) Lean supply chain strategies enhance efficiency and reduce waste:
  - Just-in-Time (JIT) inventory
  - Kanban-based replenishment
  - Lean management principles
- 8) When properly implemented, these approaches reduce holding costs while maintaining critical item availability.
- 9) Digital technologies significantly strengthen supply chain performance:
  - RFID for tracking
  - IoT for real-time monitoring
  - Blockchain for transparency
  - Artificial Intelligence for predictive optimization
- 10) These technologies enable:
  - Real-time visibility
  - Automated error detection
  - Data-driven decision-making
  - Shift from reactive to proactive management
- 11) Successful implementation requires a holistic approach, including:
  - Technical solutions
  - Organizational change management
  - Process redesign
  - Strong governance frameworks
- 12) The greatest improvements occur when hospitals adopt **supply chain optimization as a full organizational transformation**, not just system upgrades.
- 13) In the context of financial pressure and sustainability demands, supply chain excellence becomes:
  - A key driver of cost efficiency
  - A foundation for organizational resilience
  - A source of long-term strategic competitive advantage

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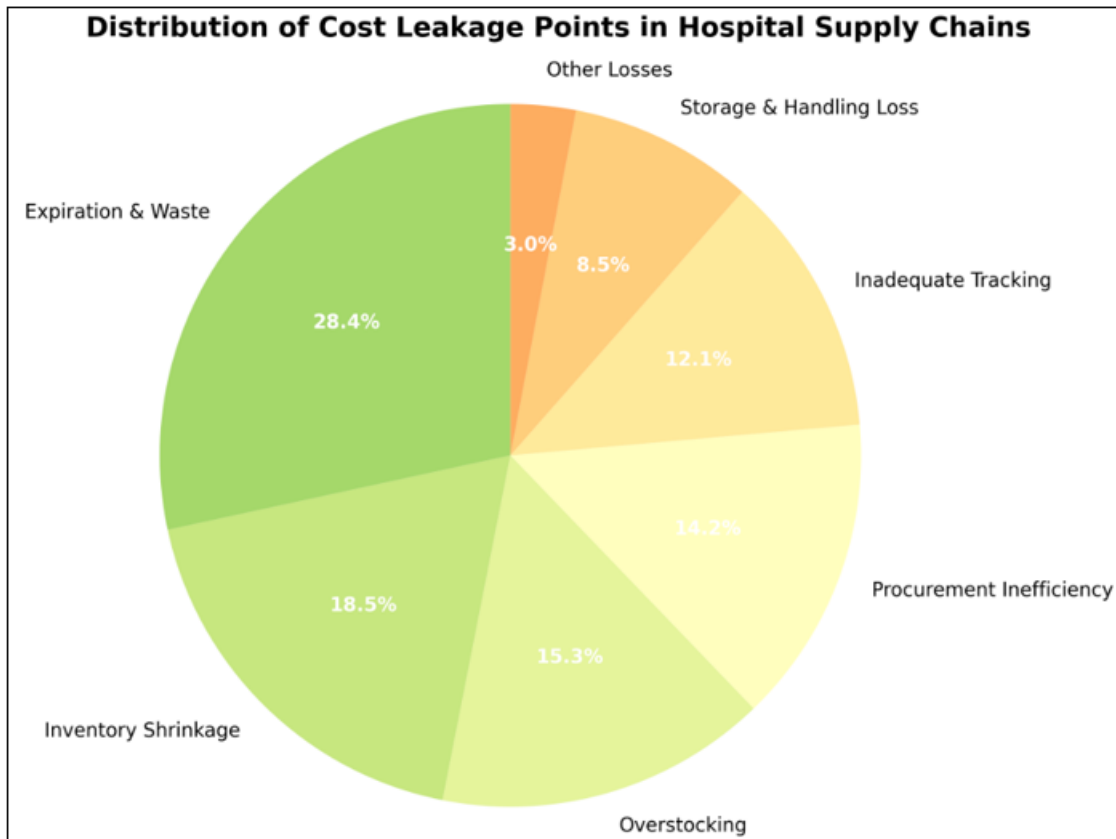
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### Visual Resources

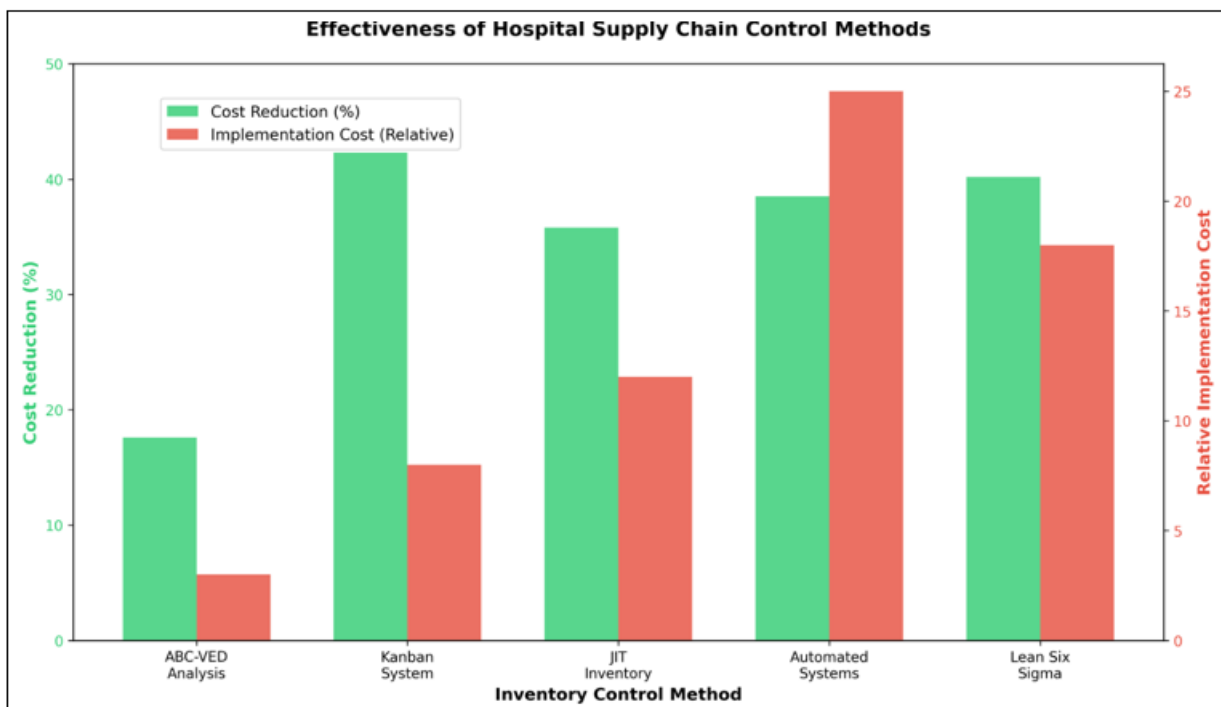
The comprehensive analysis incorporates the following visual representations:

Figure 1: Cost Leakage Points Distribution:  
 leakage\_points.png control\_methods\_effectiveness.png technology\_impact.png financial\_impact.png implementation\_timeline.png

illustrates that expiration and wastage account for the largest proportion of identifiable cost leakage, followed by inventory shrinkage and overstocking, emphasizing the critical importance of demand forecasting and tracking systems.



**Figure 2:** Control Methods Effectiveness: demonstrates that while automated systems require higher implementation investment, they deliver superior cost reductions compared to manual classification methods, with Kanban and Lean Six Sigma approaches providing optimal balance between effectiveness and implementation complexity.



**Figure 3:** Technology Impact on Performance:

reveals that integrated technology platforms combining AI, blockchain, and IoT achieve the highest performance improvements across transparency, efficiency, and fraud prevention dimensions, supporting strategic technology investment decisions.

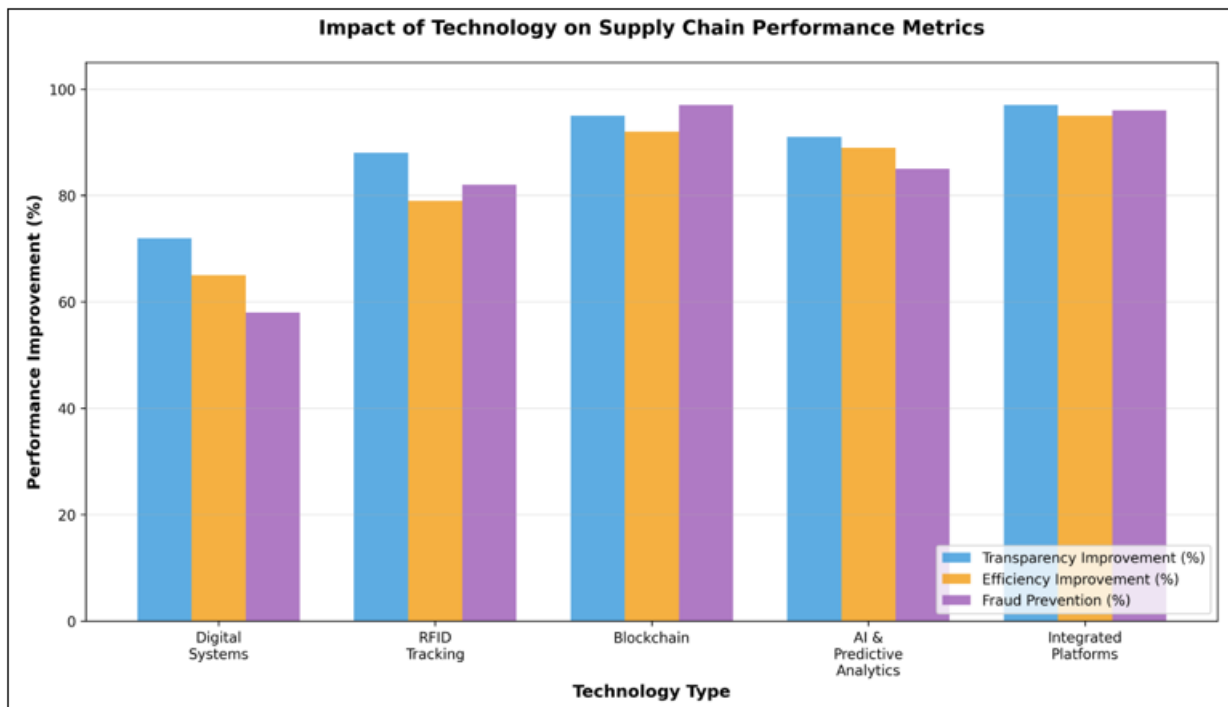


Figure 4: Financial Impact

quantifies the substantial absolute savings achievable across hospital types, with large teaching hospitals recovering \$3-4 million annually through systematic cost control implementation, while smaller hospitals recover proportionally significant amounts within their operational scales.

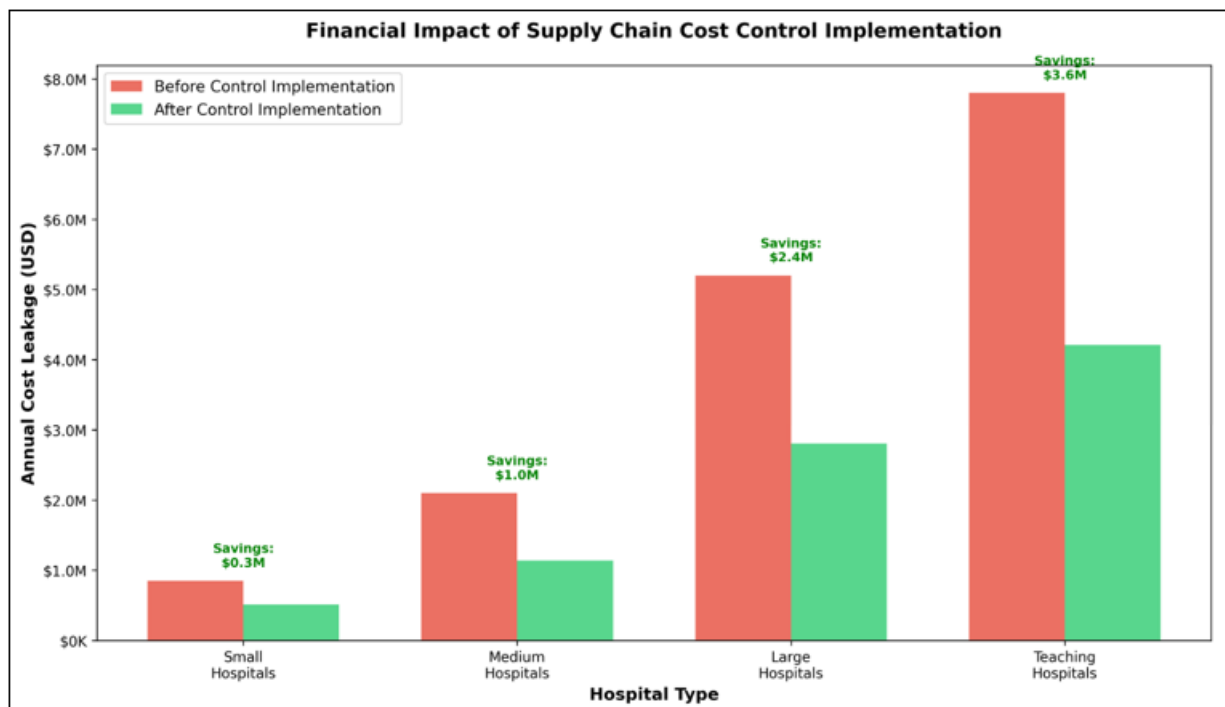
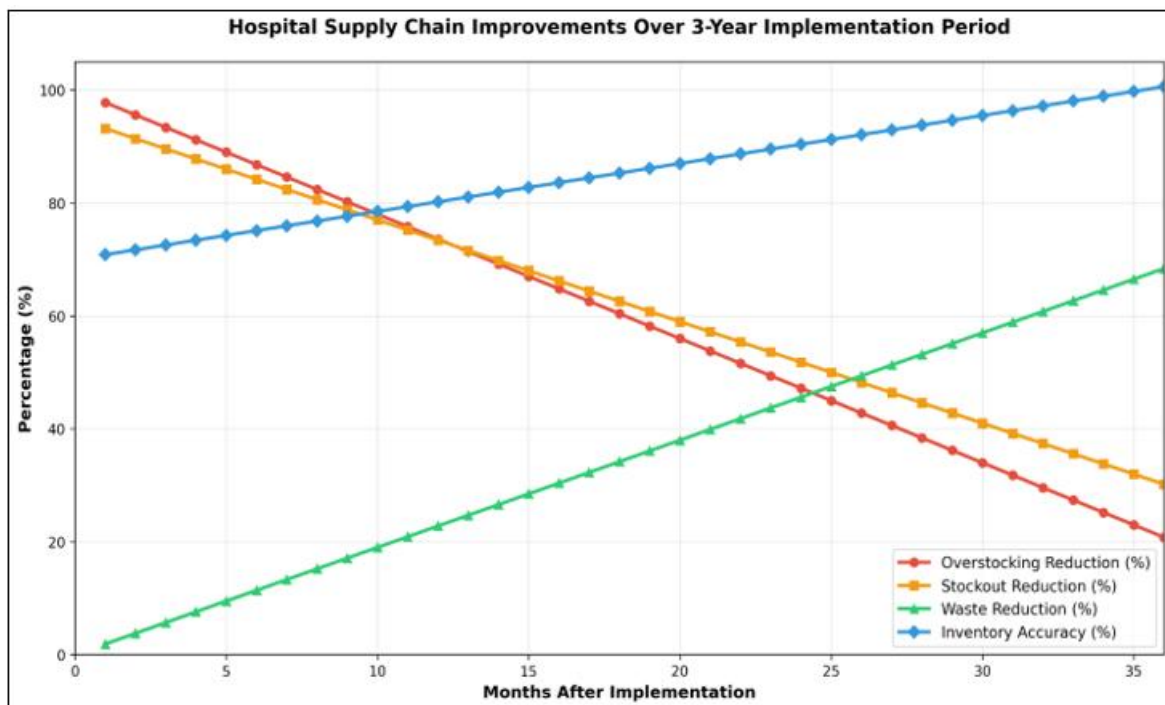


Figure 5: Implementation Timeline:

demonstrates that supply chain improvements accumulate gradually over 24-36 months, with rapid initial gains plateauing as easy-to-implement improvements are exhausted, requiring sustained commitment to achieve full optimization potential.



**Strategic Recommendations**

Healthcare organizations seeking to minimize cost leakage should pursue comprehensive, phased approaches rather than isolated interventions. Initial focus on ABC-VED classification enables rapid stratification of control intensity, while simultaneous investment in integrated information systems builds the infrastructure necessary for advanced optimization. Pilot implementation of Kanban or modified inventory systems in high-consumption categories demonstrates value and builds organizational commitment for broader deployment. Parallel investment in staff training and change management ensures that technical solutions translate into actual operational improvements. Long-term success requires treating supply chain optimization as a strategic priority with executive oversight, dedicated resources, and accountability mechanisms integrated into organizational governance.

The convergence of digital technologies- combining RFID tracking, AI-driven forecasting, blockchain transparency, and cloud-based platforms- creates unprecedented opportunities for hospital supply chain excellence. Organizations that embrace these technologies alongside process redesign and cultural transformation will achieve superior financial performance, enhanced clinical safety through more reliable availability, and improved sustainability profiles aligned with healthcare industry imperatives for environmental responsibility.

**Summary Table: Cost Leakage Points and Recommended Control Methods**

Cost Leakage Point	Primary Cause	Recommended Control Methods	Expected Cost Recovery
Expiration & Wastage	Poor forecasting, overstocking	ABC-VED analysis, JIT, Demand forecasting AI	25-35%
Inventory Shrinkage	Tracking gaps, pilferage	RFID/IoT systems, Blockchain, Regular audits	20-30%
Procurement Inefficiency	Fragmented purchasing, poor supplier management	Strategic sourcing, Vendor consolidation, Preferred suppliers	15-25%
Overstocking	Conservative safety stock policies	Dynamic safety stock optimization, ML-based forecasting	18-28%
Inadequate Tracking	Legacy systems, data silos	Integrated ERP systems, Real-time dashboards	20-32%
Storage & Handling Loss	Poor facility conditions	Environmental monitoring (IoT), Process optimization (VSM), Staff training	12-18%