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ECONOMIC MODELING OF STRATEGIC MEDICAL RESERVE SYSTEMS: COST-EFFECTIVENESS AND RESILIENCE IN HEALTHCARE EMERGENCY PREPAREDNESS

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ABSTRACT

Strategic medical reserve systems represent critical infrastructure for healthcare emergency preparedness, yet their economic evaluation remains challenging due to uncertainty, rare event characteristics, and complex benefit structures. Recent pandemic experiences have highlighted significant gaps in existing preparedness frameworks and the need for robust economic modeling approaches. This systematic review examines economic modeling approaches for strategic medical reserve systems, analyzing cost-effectiveness methodologies and resilience measurement frameworks to identify best practices and research gaps. A comprehensive literature review was conducted across multiple databases covering publications from 2000-2024. Studies were classified according to modeling approaches, application domains, and methodological frameworks. Quality assessment focused on appropriateness of economic evaluation methods and treatment of uncertainty. Traditional cost-effectiveness analysis has been substantially adapted for strategic reserve evaluation, with emerging frameworks incorporating real options theory, portfolio optimization, and simulation-based approaches. Key cost components include procurement, storage, maintenance, and opportunity costs, while benefits encompass lives saved, economic productivity preservation, and avoided healthcare system collapse. Case studies reveal tensions between cost containment and preparedness adequacy, with hybrid approaches combining physical stockpiles and production capacity reserves showing promise. Optimal strategic reserve systems require integrated economic frameworks that balance preparedness adequacy against fiscal constraints while accommodating uncertainty and resilience considerations. Future research should prioritize standardized evaluation methodologies, real-time adaptive modeling, and international coordination mechanisms. The field would benefit from increased empirical validation and development of evidence-based policy frameworks that translate complex economic analyses into actionable guidance for decision-makers.

KEYWORDS: *Strategic Medical Reserves, Health Emergency Preparedness, Cost-Effectiveness Analysis, Healthcare Resilience, Pandemic Preparedness*

1. INTRODUCTION

Strategic medical reserve systems represent critical infrastructure components designed to ensure healthcare system resilience during emergencies, pandemics, and natural disasters. These systems encompass coordinated networks of medical supplies, equipment stockpiles, human resource reserves, and logistical frameworks that can be rapidly deployed when conventional healthcare capacity is overwhelmed (Huang et al., 2024). The concept has evolved significantly from traditional civil defense preparations to comprehensive, multi-layered emergency response mechanisms that integrate both public and private sector resources.

The historical development of strategic medical reserves can be traced to the establishment of national stockpiles in response to bioterrorism threats in the early 2000s. The Strategic National Stockpile (SNS), originally called the National Pharmaceutical Stockpile (NPS), is the United States' national repository of antibiotics, vaccines, chemical antidotes, antitoxins, and other critical medical supplies. Similar initiatives have been implemented globally, with varying approaches to governance, funding, and operational frameworks. The European Health Security Committee and other international bodies have developed comparable systems, reflecting a growing recognition that health emergencies transcend national boundaries and require coordinated preparedness efforts.

Recent pandemic experiences, particularly the COVID-19 crisis, have fundamentally reshaped understanding of strategic medical reserve requirements and highlighted critical gaps in existing systems. The tragic consequences of the COVID-19 epidemic highlight to governments the importance of keeping sufficient medical supplies. Given that the physical stocks are subject to considerable obsolescence risk, existing studies have considered combining holding safety stocks with keeping production capacity or capital reserve. These experiences have demonstrated that traditional stockpiling approaches alone are insufficient and that dynamic, adaptive systems capable of rapid scaling are essential for effective emergency response.
The complexity of contemporary healthcare emergencies presents unprecedented challenges for resource allocation and

system design. Traditional approaches to emergency preparedness often rely on static stockpiling models that fail to account for the dynamic nature of modern health threats, technological obsolescence, and the interconnected nature of global supply chains. The COVID-19 pandemic revealed fundamental weaknesses in existing strategic reserve systems, including inadequate surge capacity, supply chain vulnerabilities, and coordination failures between different levels of government and private sector partners.

Improving health emergency preparedness worldwide will require substantial and sustained increases in investments. Further guidance on estimating the size of those investments can help to standardise methods, allowing greater interpretation and comparison across studies/countries. The challenge extends beyond simple resource acquisition to encompass complex trade-offs between competing objectives: maintaining adequate preparedness levels while minimizing opportunity costs, ensuring system flexibility while achieving economies of scale, and balancing centralized coordination with local autonomy.

Current decision-making frameworks often lack robust economic foundations, relying instead on ad hoc political decisions or simplistic cost-minimization approaches that fail to capture the full spectrum of costs and benefits associated with different preparedness strategies. Economic studies help decision-makers manage competing spending priorities and maximize the impact of their financial resources. The findings of economic studies can inform prevention, preparedness, response, and recovery activities in health emergency and disaster risk management. The absence of standardized economic evaluation methodologies creates significant barriers to evidence-based policy making and hampers efforts to optimize resource allocation across different preparedness activities.

This review aims to provide a comprehensive analysis of economic modeling approaches for strategic medical reserve systems, with particular emphasis on cost-effectiveness evaluation and resilience measurement. The primary objectives include: (1) systematically reviewing existing economic modeling frameworks applied to medical reserve systems; (2) analyzing methodological approaches for measuring cost-effectiveness in emergency preparedness contexts; (3) examining frameworks for quantifying and integrating resilience considerations into economic models; and (4) identifying key research gaps and future directions for advancing the field.
The review focuses on strategic reserves specifically designed for medical emergencies, including pandemic preparedness, bioterrorism response, and natural disaster medical support. While broader emergency management topics are considered where relevant, the primary emphasis remains on healthcare-specific applications and the unique characteristics of medical supply chains, clinical workforce considerations, and health system integration challenges. The temporal scope covers developments from the establishment of modern strategic reserves in the early 2000s through the most recent post-COVID-19 innovations and policy adaptations.

2. METHODOLOGY

This systematic literature review adhered to best practices in health economics, aiming to capture both theoretical and empirical studies on the economic modeling of strategic medical reserves.

Search Strategy: A broad, structured search was conducted across key databases (e.g., PubMed, Embase, EconLit, Web of Science, Cochrane Library, CEA Registry, HTA database) using refined search terms related to strategic medical reserves and economic evaluation. The review covered English-language studies from 2000–2024 with no geographic limitations.

Inclusion/Exclusion Criteria: Studies were included if they focused on economic aspects of medical emergency preparedness, such as cost-effectiveness or resource allocation. The review prioritized original research and substantial methodological papers. Exclusions applied to studies lacking economic focus, clinical-only analyses, or insufficient system-level relevance.
Quality Assessment: Using adapted frameworks like CHEERS and CASP, studies were evaluated for methodological rigor, policy relevance, and ability to handle emergency-specific challenges such as uncertainty and rare events. The robustness of data sources, relevance of context, and transparency of assumptions were key assessment criteria.

Classification Framework: A taxonomy was created to categorize modeling approaches (e.g., cost-effectiveness, simulation, financial models, multi-criteria decision analysis) and their application domains (e.g., pandemics, bioterrorism, natural disasters). Models were further classified by scope (national vs. local), system integration level, and temporal context (immediate to long-term response).

3. ECONOMIC MODELING APPROACHES

3.1 Traditional Cost-Effectiveness Models

Traditional cost-effectiveness analysis (CEA) frameworks have been adapted for strategic medical reserve evaluation, although their application presents unique methodological challenges compared to conventional healthcare interventions. The fundamental principles of CEA remain applicable, but the temporal uncertainty, probabilistic nature of benefits, and complex stakeholder considerations require significant methodological adaptations.

Cost-Effectiveness Analysis (CEA) Applications: Cost-Effectiveness Analysis (CEA) Applications in strategic reserve contexts focus on comparing alternative preparedness strategies in terms of costs per life-year saved, quality-adjusted life-years (QALYs) gained, or other relevant health outcomes. Cost-effectiveness analyses generate incremental cost-effectiveness ratios for comparison against per-capita gross domestic product thresholds to determine cost-effectiveness, with studies showing that indirect costs were greater than direct costs mainly due to losses of productivity (Singh et al., 2021). These applications typically involve scenario-based analyses that estimate the expected benefits of different preparedness investments across multiple possible emergency scenarios.

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The adaptation of CEA to strategic reserves requires careful consideration of baseline comparators, as "no preparedness" scenarios are often politically unacceptable and ethically problematic. Instead, analyses typically compare incremental improvements to existing preparedness levels or alternative preparedness strategies. The time horizon for analysis presents particular challenges, as preparedness investments may provide benefits over decades while facing ongoing maintenance costs and periodic updating requirements.

Cost-Utility Analysis in Emergency Preparedness: Cost-Utility Analysis in Emergency Preparedness extends traditional CEA by incorporating quality-of-life considerations through measures such as QALYs or disability-adjusted life-years (DALYs). This approach proves particularly valuable for strategic reserve evaluations because emergency preparedness investments often prevent not only deaths but also significant morbidity, psychological trauma, and social disruption that pure mortality-based measures fail to capture.

The application of utility measures in emergency contexts raises conceptual challenges regarding the appropriate time perspective and the treatment of uncertainty. Unlike clinical interventions with well-established utility weights, emergency preparedness involves rare events with potentially catastrophic consequences that may not be adequately captured by standard utility measurement approaches. Recent methodological developments have explored the use of stated preference methods and discrete choice experiments to elicit utility weights specific to emergency preparedness contexts.

Budget Impact Models: Budget Impact Models focus on the financial implications of strategic reserve investments for healthcare systems, government budgets, and society more broadly. These models are particularly relevant for policy decision-making as they provide direct estimates of resource requirements and cash flow implications. Budget impact modeling for strategic reserves must account for the lumpy nature of preparedness investments, where large upfront costs may be followed by relatively low maintenance expenses punctuated by periodic replenishment or modernization requirements.

The temporal profile of budget impacts presents unique modeling challenges, as preparedness investments may require sustained funding commitments over extended periods while providing benefits only during emergency activation. This creates particular difficulties for budget planning and political sustainability, as preparedness expenditures may be viewed as discretionary during non-emergency periods.

3.2. Advanced Modeling Techniques

Advanced economic modeling techniques have emerged to address the limitations of traditional health economic evaluation methods when applied to strategic reserve systems. These approaches explicitly account for uncertainty, flexibility, and the option value of maintaining emergency response capabilities.

Real Options Theory: Real Options Theory Applications provide frameworks for valuing the flexibility inherent in strategic reserve systems. Real options analysis applies option valuation techniques to capital budgeting decisions, with studies showing that optimal reserve policies should be determined by joint consideration of safety stocks, production capacity, and capital reserves, particularly given that physical stocks are subject to considerable obsolescence risk (Huang et al., 2024; Zhang et al., 2021). This approach recognizes that strategic reserves create valuable options that can be exercised during emergencies, even when the probability and timing of such emergencies remain uncertain.

Real options applications in strategic reserve contexts typically focus on valuing the flexibility to scale response capacity, the ability to defer investment decisions pending better information, and the option to abandon or repurpose preparedness investments if threat assessments change. The approach is particularly valuable for evaluating modular reserve systems that can be expanded or contracted based on evolving threat assessments and resource availability.

Portfolio Optimization Models: Portfolio Optimization Models treat strategic reserve investments as components of broader emergency preparedness portfolios, seeking to optimize risk-adjusted returns across multiple preparedness activities. These models explicitly account for correlation structures between different types of emergencies and the complementarities between different preparedness investments. Modern portfolio theory concepts such as diversification, risk-return optimization, and correlation analysis provide frameworks for balancing preparedness investments across different threat categories.

The application of portfolio optimization to strategic reserves requires careful specification of risk measures and return metrics. Risk measures may include expected casualties, economic losses, or system disruption metrics, while returns encompass the risk reduction benefits provided by different preparedness investments. The challenge lies in developing appropriate probability distributions and correlation structures for rare events with limited historical data.

Dynamic Programming: Dynamic Programming Approaches address the sequential nature of strategic reserve decisions, where current investment choices affect future options and constraints. These models recognize that preparedness decisions unfold over time, with new information becoming available that may affect optimal strategies. Dynamic programming frameworks provide methods for optimizing sequential decision-making under uncertainty while accounting for path dependence and learning effects.
Applications include optimal inventory replacement policies that balance obsolescence risks against stockout probabilities, capacity expansion decisions that consider evolving threat assessments and technological changes, and resource allocation strategies that adapt to changing political priorities and budget constraints.

3.3. Simulation and Stochastic Models

Simulation-based approaches have become increasingly important for strategic reserve economic evaluation, particularly as computing power has increased and modeling software has become more accessible. These methods enable analysis of complex systems with multiple interactions, feedback loops, and stochastic elements that are difficult to capture in closed-form analytical models.

Monte Carlo Simulation Methods: Monte Carlo Simulation Methods provide frameworks for incorporating uncertainty into economic evaluations through probabilistic sensitivity analysis. These approaches assign probability distributions to key model parameters and use random sampling to generate ranges of possible outcomes. For strategic reserve applications, Monte Carlo methods are particularly valuable for incorporating uncertainty about emergency probability, magnitude, and timing, as well as uncertainty about intervention effectiveness and cost parameters.

Recent applications have used Monte Carlo methods to evaluate the robustness of strategic reserve recommendations across different assumptions about threat scenarios, to quantify the value of information for reducing key uncertainties, and to optimize reserve sizing decisions under probabilistic demand scenarios. The approach enables explicit quantification of decision uncertainty and provides risk profiles that are valuable for policy decision-making.

Discrete Event Simulation models: Discrete Event Simulation models emergency response systems as sequences of discrete events occurring over time, with system state changes triggered by event occurrences. These models are particularly suitable for analyzing operational aspects of strategic reserve systems, including resource flow dynamics, bottleneck identification, and performance optimization under different demand scenarios.

Applications include modeling the deployment of strategic reserves during emergencies, analyzing the interaction between federal, state, and local response systems, and evaluating the performance of different distribution strategies under varying emergency characteristics. The approach enables detailed analysis of system performance metrics such as response times, coverage rates, and resource utilization efficiency.

Agent-Based Modeling Applications: Agent-Based Modeling Applications represent strategic reserve systems as collections of autonomous agents (government agencies, healthcare institutions, private sector partners) that interact according to specified rules and behavioral patterns. This approach is particularly valuable for analyzing coordination challenges, information flow dynamics, and emergent system behaviors that arise from decentralized decision-making.

Recent applications have used agent-based models to analyze the effectiveness of different coordination mechanisms, to evaluate the impact of information sharing policies on system performance, and to study the emergence of cooperation and competition dynamics among different stakeholders in emergency response networks. The approach provides insights into system-level properties that emerge from individual agent behaviors and interactions.

4. COST COMPONENTS AND VALUATION METHODS

4.1 Direct Costs

The comprehensive assessment of strategic medical reserve systems requires careful categorization and valuation of multiple cost components, each presenting unique measurement challenges. Direct costs represent the most tangible and readily quantifiable elements of strategic reserve investments, though their accurate estimation requires sophisticated accounting frameworks that capture both obvious expenditures and less visible operational costs.

Procurement and Stockpiling Costs constitute the most visible component of strategic reserve expenditures. Recent experience demonstrates the magnitude of these investments, with New York State spending $452.8 million to purchase 247,343 items of durable medical equipment (DME) during the onset of COVID-19. These procurement costs extend beyond simple purchase prices to encompass complex contracting arrangements, quality assurance procedures, and coordination costs associated with rapid acquisition during emergency conditions.

The procurement cost structure varies significantly between routine stockpile maintenance and emergency acquisition periods. Routine procurement typically benefits from competitive bidding processes, bulk purchasing advantages, and stable market conditions that enable cost optimization. Emergency procurement, conversely, often occurs under extreme time constraints with limited supplier options and inflated market prices due to surge demand across multiple purchasers simultaneously.

Strategic reserve systems increasingly recognize the importance of procurement cost volatility and the need for flexible contracting arrangements that can accommodate both routine maintenance and surge acquisition scenarios. This includes establishing pre-negotiated contracts with suppliers, maintaining vendor qualification systems that enable rapid procurement during emergencies, and developing cost estimation models that account for market disruption effects.

Storage and Maintenance Expenses represent ongoing costs that accumulate throughout the operational life of strategic reserves. These expenses encompass facility costs including real estate, utilities, and security systems; specialized storage requirements such as cold chain maintenance for vaccines and temperature-controlled environments for pharmaceuticals; and regular maintenance activities including inventory rotation, equipment testing, and facility upgrades.

The storage cost structure presents particular challenges for economic evaluation because these expenses continue regardless of whether reserves are ever utilized. Unlike conventional healthcare investments where utilization directly correlates with benefit generation, strategic reserves incur storage costs as insurance premiums against uncertain future events. This characteristic necessitates careful attention to cost allocation methods and the temporal distribution of expenses in economic models.

Modern storage approaches increasingly emphasize distributed storage networks that balance cost efficiency against resilience considerations. Centralized storage offers economies of scale and simplified management but creates vulnerability to localized disruptions. Distributed approaches increase storage costs but enhance system resilience and reduce transportation costs during deployment.

Technology and Infrastructure Investments encompass the capital expenditures required to establish and maintain strategic reserve capabilities. This includes information technology systems for inventory management and tracking, specialized equipment for storage and distribution, transportation assets for deployment, and communication systems for coordination during emergencies.

Technology investments present particular valuation challenges due to rapid obsolescence rates and the need for periodic upgrades to maintain interoperability with evolving healthcare systems. The useful life of technology components often differs significantly from the operational life of strategic reserves, requiring careful consideration of replacement cycles and upgrade costs in economic evaluations.

4.2. Indirect and Opportunity Costs

The economic evaluation of strategic medical reserves extends beyond direct expenditures to encompass complex indirect costs and opportunity costs that may represent substantial portions of total system costs. These cost categories prove particularly challenging to quantify but are essential for accurate economic assessment.

Obsolescence and Wastage Costs represent significant economic impacts specific to strategic reserve systems. Medical supplies and pharmaceuticals have limited shelf lives, requiring periodic replacement even when reserves are never deployed. This creates ongoing costs that must be balanced against the insurance value provided by maintaining stockpiles. Obsolescence costs vary significantly across different product categories, with some pharmaceuticals requiring replacement every few years while durable medical equipment may maintain utility for decades.

The COVID-19 pandemic highlighted the challenge of balancing obsolescence risks against preparedness benefits. Recent supply chain disruptions have caused delays in component and raw material deliveries, leading to stock management challenges at an estimated total cost of $150 million, with shipping costs rising by 15-20% due to rerouting of maritime routes. These disruptions demonstrate how external factors can dramatically increase the costs associated with maintaining strategic reserves.

Alternative Use of Resources encompasses the opportunity costs associated with committing resources to strategic reserves rather than alternative uses. This includes both financial opportunity costs from capital tied up in reserve investments and physical opportunity costs from storage facilities and personnel dedicated to reserve management rather than other activities.

The opportunity cost calculation requires explicit consideration of alternative investments that could be made with the same resources. In healthcare contexts, this often involves comparing strategic reserve investments against direct patient care improvements, routine public health programs, or other emergency preparedness activities. The challenge lies in developing appropriate counterfactual scenarios and ensuring that opportunity cost estimates reflect realistic alternative uses.

Administrative and Coordination Costs encompass the personnel, organizational, and coordination expenses required to maintain strategic reserve systems. These costs include dedicated staff for system management, coordination mechanisms between different government levels and private sector partners, training programs for reserve deployment, and ongoing planning and exercise activities.

Coordination costs prove particularly significant in strategic reserve systems due to their multi-stakeholder nature and the complexity of emergency deployment procedures. Effective reserve systems require coordination across federal, state, and local government levels; integration with private sector suppliers and healthcare providers; and ongoing communication with potential users and beneficiaries.

4.3. Benefit Valuation Challenges

The economic evaluation of strategic medical reserves faces unique challenges in quantifying and monetizing benefits, particularly given the probabilistic nature of emergency events and the diverse types of benefits that reserve systems provide.

Lives Saved and Quality-Adjusted Life Years represent the primary health outcomes for strategic reserve economic evaluation. The quality-adjusted life year (QALY) is the gold standard for measuring how well all different kinds of medical treatments lengthen and/or improve patients' lives, and has served as a fundamental component of cost-effectiveness analyses in the US and around the world for more than 30 years.

The application of QALY methods to strategic reserves presents several methodological challenges. Standard QALY calculations assume well-defined patient populations with established baseline health states and predictable treatment effects. Strategic reserves, conversely, address uncertain future populations facing unknown health threats with interventions of uncertain effectiveness. This requires adaptation of standard QALY methods to accommodate scenario-based analysis and probabilistic benefit estimation.

Recent research has explored various approaches to QALY valuation in emergency preparedness contexts. One notable example found that the cost-effectiveness of kidney dialysis implied a value of about US$129,000 per quality-adjusted life year (QALY), providing benchmarks for evaluating emergency preparedness investments. However, the translation of such benchmarks to emergency preparedness contexts requires careful consideration of the different risk profiles and utility considerations that characterize emergency versus routine healthcare scenarios.

Economic Productivity Preservation encompasses the broader economic benefits that strategic reserves provide by preventing or reducing economic disruption during health emergencies. These benefits extend beyond direct health outcomes to include maintained economic activity, preserved employment, and avoided business disruption costs.

The Environmental Protection Agency has estimated an economic present value of $9.5 million per life saved, providing one approach to monetizing the economic benefits of life-saving interventions. However, the application of such values to strategic reserve evaluation requires careful consideration of the age and health characteristics of populations most likely to benefit from emergency preparedness investments.

Avoided Healthcare System Collapse Costs represent perhaps the most significant but most difficult to quantify benefits of strategic medical reserves. Healthcare system collapse during emergencies creates cascading effects that extend far beyond direct mortality impacts to encompass the inability to provide routine care, loss of healthcare workforce, and long-term damage to healthcare infrastructure and capabilities.

The COVID-19 pandemic provided unprecedented insights into healthcare system collapse costs, with a 17.5% increase in overall hospital expenses between 2019 and 2022 and hospitals' labor costs increasing by more than $42.5 billion between 2021 and 2023 to a total of $839 billion. These experiences demonstrate the magnitude of costs associated with healthcare system stress and provide empirical foundations for estimating the benefits of strategic reserves in preventing or mitigating such outcomes.

The challenge lies in developing methods to attribute system collapse costs to the absence of adequate strategic reserves and to estimate the extent to which different reserve configurations could prevent or reduce such costs. This requires sophisticated modeling approaches that can capture the complex interactions between reserve availability, system capacity, and emergency characteristics.

5. CASE STUDIES AND APPLICATIONS

5.1. National Strategic Reserves

United States Strategic National Stockpile represents the most extensively studied national reserve system. The United States maintains a stockpile of drugs, vaccines, and other medical supplies to provide for the nation's emergency health security, with over $8 billion worth of inventory (Council on Foreign Relations, 2023). The COVID-19 pandemic exposed significant limitations, as the Stockpile was operationally effective in distributing its limited inventory but its strategic effectiveness and its ability to meet COVID-19 demands were inadequate (U.S. Department of Health and Human Services, 2024; NBC News, 2022).

Economic analyses reveal the tension between cost containment and preparedness adequacy. The SNS's bioterrorism-focused design proved insufficient for pandemic response, highlighting the need for all-hazards approaches that balance specificity against flexibility.

European Health Security Committee Initiatives demonstrate alternative organizational models. The EU's rescEU medical stocks represent coordinated multinational reserves that pool resources across member states while maintaining national sovereignty over deployment decisions (European Commission, 2023). This approach offers cost-sharing benefits but creates coordination complexities that affect response speed and effectiveness.

Other International Examples include South Korea's strategic reserves, which proved effective during COVID-19 through rapid mobilization of domestic production capacity combined with strategic stockpiles, and Australia's National Medical Stockpile, which emphasizes distributed storage and regional coordination mechanisms.

5.2. Regional and Local Systems

Hospital Surge Capacity Planning integrates strategic reserves with operational healthcare capacity. Economic models demonstrate trade-offs between maintaining excess capacity during normal operations versus relying on external reserves during emergencies (RAND Corporation, 2020). Cost-effectiveness varies significantly based on local threat profiles and baseline capacity utilization rates.

Regional Medical Response Networks coordinate multiple hospitals and healthcare systems to create shared reserve capabilities. These models reduce individual institution costs while maintaining collective surge capacity, though they require sophisticated coordination mechanisms and shared governance structures.

Supply Chain Resilience Initiatives emphasize upstream interventions that maintain production capacity rather than finished product stockpiles. Economic analyses suggest these approaches may offer superior cost-effectiveness for certain product categories, particularly when combined with rapid production scaling capabilities (Zhang et al., 2021).

5.3. Pandemic-Specific Applications

COVID-19 Response Economic Analyses provide unprecedented empirical data on strategic reserve performance (Singh et al., 2021). Studies document both the costs of inadequate preparedness and the economic benefits of rapid scaling. Healthcare system expenditures increased 17.5% between 2019-2022, with labor costs rising over $42.5 billion, demonstrating the economic magnitude of inadequate preparedness.

Influenza Preparedness Models offer mature frameworks for pandemic economic evaluation. These models typically focus on vaccine stockpiling and antiviral distribution, with well-established cost-effectiveness benchmarks that inform preparedness investment decisions.

Emerging Infectious Disease Frameworks address uncertainty about future pandemic characteristics through scenario-based modeling approaches (Huang et al., 2024). These frameworks emphasize flexibility and rapid adaptation capabilities rather than threat-specific preparations.

6. FUTURE DIRECTIONS AND RESEARCH GAPS

Recent advancements in strategic medical reserve planning emphasize methodological innovations, policy integration, and emerging global challenges. The integration of AI and machine learning offers transformative potential for optimizing resource allocation, demand forecasting, and emergency deployment. Real-time adaptive modeling, using continuous data updates, enhances responsiveness, while incorporating behavioral economics helps capture human decision-making under stress. For policy and practice, translating complex models into actionable guidance requires standardized evaluation frameworks, regular reviews, and implementation science to bridge theory-practice gaps. Effective strategies must address organizational, political, and technical barriers, while improving stakeholder engagement through inclusive, cross-sectoral planning. Emerging challenges like climate change, cybersecurity threats, and global supply chain fragility demand updated models that reflect evolving health risks, digital vulnerabilities, and international interdependencies.

7. CONCLUSION

This systematic review highlights the evolving nature of economic modeling for strategic medical reserves, shaped by recent pandemics. Traditional cost-effectiveness models have expanded to address uncertainty, resilience, and multi-stakeholder needs. Hybrid systems—combining stockpiles, production capacity, and flexible coordination—are found to be more effective than stockpiling or market-based approaches alone. Integrating resilience into economic evaluation is a key advancement, though measuring it remains challenging. The review calls for standardized metrics, more empirical validation, and adaptive modeling frameworks. Policy implications stress the need for evidence-based investment tools that balance preparedness with budget constraints. Future research should explore innovative methods incorporating technology, behavioral factors, and shifting threat landscapes, alongside enhanced international collaboration and standardized evaluation criteria.

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