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Article

Research on Data-Sharing Mechanisms and Value Chain Reconfiguration in the Macao--Hengqin Collaborative "Big Health" Industry

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Abstract: This paper examines how cross-border data-sharing between Macao and Hengqin ("Macao--Hengqin collaboration") can catalyze value chain reconfiguration in the Big Health industry spanning biomedicine, medical devices, digital health, wellness tourism, and elderly care. A governance-ready framework is proposed that aligns interoperable data infrastructure with clinical, industrial, and tourism-service workflows, integrating privacy-preserving technologies, trustable exchange rules, and outcome-oriented incentives. The study develops a five-layer architecture—data, features, analytics and forecasting, coordination and optimization, and risk-and-compliance—that links micro-level data flows to meso-level cluster synergies and macro-level productivity and competitiveness. Within this architecture, federated learning, tokenized data assets, and standardized interfaces are used to support secure cross-border collaboration in research and development, clinical trials, and service delivery. A semi-synthetic evaluation calibrated to Greater Bay Area statistics suggests that federated and tokenized data-sharing can shorten R&D cycles, increase cross-border patient recruitment efficiency, and elevate service export value while controlling privacy risk and regulatory exposure. The analysis further highlights institutional frictions, interoperability gaps, and governance challenges that may constrain implementation. In response, policy and operational strategies are proposed for platform design, standard harmonization, regulatory sandboxes, and public–private partnerships to realize sustained industrial upgrading, promote regional integration, and enhance the global competitiveness of the Macao–Hengqin Big Health cluster.

Keywords: health industry; data sharing; value chains; regional integration; governance; innovation policy

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1. Introduction

1.1. Background and Significance

Macao's service-led economy, distinguished by its advanced tourism infrastructure, exceptional hospitality services, and well-established medical tourism sector, aligns synergistically with Hengqin's extensive land resources, sophisticated manufacturing capabilities, and seamless access to mainland regulatory and healthcare systems. This strategic combination of complementary strengths provides a unique opportunity to develop a cross-border Big Health cluster encompassing biomedical research, medical device innovation, clinical services, and wellness tourism. Despite these advantages, the lack of integrated and interoperable data systems across hospitals, contract research organizations (CROs), device manufacturers, insurers, and tourism operators creates significant barriers. Fragmented and isolated datasets hinder translational research, delay

clinical trial recruitment, limit the design of precision services, and obstruct the development of unified cross-border reimbursement mechanisms. Addressing these challenges requires the implementation of structured data-sharing frameworks and collaborative governance models that prioritize security and privacy [1]. By establishing such frameworks, the region can unlock its full potential, accelerating research and development timelines, improving the quality of patient and tourist care, optimizing resource utilization, and expanding service exports. This approach would not only support Macao's efforts toward moderate economic diversification but also advance Hengqin's goals of deeper integration and industrial upgrading, fostering sustainable regional growth.

1.2. Literature Landscape and Gaps

Prior research has thoroughly explored healthcare data interoperability, privacy-preserving analytics, and industrial clustering within health ecosystems, highlighting the advantages of federated learning, standardization, and collaborative platforms [2]. However, significant gaps remain in addressing cross-jurisdictional governance challenges, particularly in regions with distinct legal frameworks such as Macao and the mainland. Key areas requiring further investigation include service trade integration, aligning incentives among diverse stakeholders, and operationalizing data-sharing mechanisms to achieve measurable improvements across value chains. Practical obstacles involve harmonizing data and technical standards across varying regulatory environments, developing equitable pricing and reward systems for contributions from heterogeneous participants, ensuring real-time compliance and auditability, and linking collaborative analytics to concrete outcomes such as enhanced clinical efficiency, improved trial performance, higher precision in service quality, and increased tourism revenue. This paper aims to bridge these gaps by proposing a practical, evaluation-ready architecture, establishing performance metrics focused on outcomes, and creating a strategic toolkit tailored to the Macao-Hengqin Big Health ecosystem. The proposed framework seeks to enable coordinated innovation, ensure compliance, and foster cross-border value creation, addressing both technical and governance challenges in a holistic manner.

2. Conceptual Framework and Problem Definition

2.1. Objectives and Constraints

The primary objective of the framework is to optimize collaborative value creation across the interconnected ecosystem of biopharma, medical devices, clinical research, and wellness tourism. This involves achieving measurable targets such as reducing research and development timelines for pharmaceuticals and medical devices, enhancing the efficiency of patient recruitment in clinical trials, advancing the precision and personalization of medical services, and increasing revenue streams from wellness and medical tourism. These ambitious goals must be pursued while navigating a complex array of constraints, including safeguarding patient privacy, adhering to cross-border data localization regulations, upholding medical ethics, protecting intellectual property rights, and complying with diverse regulatory requirements across different jurisdictions. The framework is designed to address behavioral and contractual challenges among varied stakeholders, including hospitals, contract research organizations, start-ups, pharmaceutical and device companies, insurers, and tourism operators. Operational safeguards are implemented to ensure informed consent protocols, purpose-specific data usage, minimization of sensitive data exposure, auditable interactions, and equitable data access. These measures aim to foster collaboration that generates value while maintaining trust, compliance, and adherence to ethical standards.

2.2. Data-Sharing Externalities and Value Chain Transmission

Data sharing within this multi-stakeholder ecosystem fosters significant positive externalities, which substantially enhance value creation across various domains. The integration of multi-source datasets contributes to the improved generalization of machine learning models, enabling more accurate predictions and insights. This process also accelerates the discovery of biomarkers, which are critical for advancing personalized medicine, and supports the ongoing monitoring of medical devices after they enter the market. Furthermore, network effects in service matching play a pivotal role in increasing the utilization of healthcare facilities, improving the efficiency of clinical trial sites, and optimizing patient distribution across different regions. Key mechanisms driving these benefits include federated analytics, which enable cross-site target discovery and the design of adaptive clinical trials; the facilitation of cross-border patient flows, which enrich datasets and support the development of customized health-tourism packages; access for insurers to de-identified clinical and outcomes data, which allows for more precise product pricing and risk evaluation; and the use of multi-site real-world evidence by device manufacturers to streamline regulatory approval processes and enhance post-market surveillance. However, without robust governance frameworks, significant risks may arise, including privacy breaches, inconsistent consent management practices, misaligned technical standards, and disparities in bargaining power. These challenges can undermine trust, discourage participation, and ultimately diminish the collaborative advantages that the ecosystem aims to achieve.

2.3. Architecture for Collaborative Data-Driven Upgrading

To operationalize these objectives, a comprehensive five-layer architecture is implemented to ensure seamless integration and functionality [3]. The data layer is designed to aggregate diverse and heterogeneous sources, encompassing clinical records such as EHR and EMR, imaging data, omics and genetic information, device telemetry, pharmacy and claims data, as well as logs from wellness and tourism services. Additionally, it includes supply-chain and quality-related information, all meticulously cataloged with immutable logging to ensure traceability and data integrity. The feature layer focuses on encoding critical attributes such as patient phenotypes, trial eligibility criteria, device performance metrics, provider capacity, tourism preferences, and cost-quality indicators. This layer also enforces strict temporal lags to mitigate risks of data leakage and ensure robust analytical outcomes. The analytics and forecasting layer is equipped to facilitate advanced functionalities, including cohort discovery, demand forecasting, cost-quality trade-off modeling, safety signal detection, and scenario analysis. These capabilities are underpinned by privacy-preserving computation techniques, enabling actionable insights without compromising sensitive data. The coordination and optimization layer translates these insights into actionable strategies by aligning clinical trials with appropriate sites, designing patient referral systems and tourism packages, managing cross-border capacity, and optimizing procurement and inventory through advanced multi-objective optimization techniques. Lastly, the risk-and-compliance layer ensures adherence to stringent standards by implementing consent management, purpose limitation, dynamic de-identification, controlled access governance, explainable decision-making processes, and cross-jurisdictional audit mechanisms. This architecture not only drives value creation but also upholds legal, ethical, and operational standards across the collaborative ecosystem [4].

3. Data and Measurement Strategy

3.1. Sources, Governance, and Traceability

Data sources encompass a wide range of domains, including clinical, industrial, payer, and tourism sectors, to facilitate comprehensive value creation across biopharma, medical device, and wellness tourism ecosystems. Clinical data is derived from hospitals and specialty clinics in Macao and Hengqin, clinical trial management systems operated

by contract research organizations, patient registries, laboratory and imaging centers, and telemedicine platforms. Industrial data sources include device quality management systems, manufacturing execution systems, supervisory control and data acquisition logs, logistics tracking systems, and after-sales service records. Payer data integrates information from commercial insurers' claims, cross-border reimbursement records, and benefit adjudication processes. Tourism-related data includes booking records, itinerary details, customer satisfaction logs, feedback reports, and occupancy analytics. Governance mechanisms are structured around a joint data stewardship council that ensures coordination of standards, a shared metadata catalog for harmonizing terminology, and dynamic consent registries that allow patients to revoke authorization [5, 6]. Data-use agreements are explicitly aligned with specific purpose codes. Advanced technologies such as hashing and digital watermarking are employed to ensure data provenance and tamper resistance. Privacy-preserving computation methods include federated learning for model training without raw data transfer, secure enclaves for sensitive computations, and differential privacy for aggregated outputs. Cross-border gateways enforce policy-as-code to ensure compliance with jurisdiction-specific privacy and data localization requirements.

3.2. Outcome and Efficiency Metrics

Outcome metrics are essential for evaluating clinical, operational, and economic performance comprehensively. Clinical outcomes encompass measures such as the time required to progress from research and development to regulatory submissions, conversion rates from trial screening to randomization, and the speed of detecting adverse events. Service quality is assessed using precision indicators, including readmission rates, patient-reported outcome measures, and health-related quality-of-life scores. Operational efficiency metrics focus on factors like the utilization rates of beds and medical devices, insurer loss ratios, and revenue generated per visitor-day in medical tourism. Efficiency is further analyzed through marginal improvements, such as the time saved with each additional federated site, the incremental increase in precision with new data modalities, the turnaround time for cross-border referrals, and the inventory turnover rates in pharmaceutical and device supply chains. Equity and inclusion are evaluated by examining the breadth of cohort coverage and the latency in access between resident and non-resident groups, ensuring that collaborative efforts promote fairness and do not exacerbate disparities. These metrics collectively enable a holistic assessment of value creation and stakeholder equity.

3.3. Validation Protocol and Benchmarking

Validation employs a comprehensive and multi-dimensional protocol designed to ensure robustness and adaptability across diverse scenarios. The rolling-origin evaluation method incorporates regime-aware blocking to account for temporal shifts, particularly around changes in policies or operational frameworks. This approach enhances the reliability of the validation process under evolving regulatory or contextual conditions. Site-level cross-validation is utilized to test the model's ability to generalize across varied clinical and industrial environments, ensuring applicability in heterogeneous settings. Synthetic data augmentation is applied to simulate privacy-preserving linkages and evaluate model resilience when faced with sparse or incomplete datasets [7, 8]. Benchmarking involves comparing siloed analytics, pooled-centralized models (where permissible), and federated learning configurations using equivalent model families. Key metrics tracked include predictive accuracy, calibration, privacy-loss budgets, operational performance indicators, and compliance incident rates. Decision-focused evaluations further analyze shifts in cost-quality trade-offs, service-export contributions, and resource allocation efficiency, offering actionable insights for operational improvements and strategic policy development. Collectively, these protocols ensure the framework delivers equitable, measurable, and auditable benefits across multi-stakeholder ecosystems.

4. Methodology

4.1. Privacy-Preserving Analytics and Interoperability

Federated learning facilitates collaborative model training across nodes in Macao and Hengqin without the need to transfer raw data, thereby ensuring the preservation of local privacy while harnessing distributed intelligence. This approach employs advanced techniques such as secure aggregation, which enables the combination of model updates without exposing individual contributions. Additionally, client selection strategies are utilized to address variations in data quality across different sources, while drift detection mechanisms are implemented to identify and mitigate temporal or demographic changes that could negatively impact model performance. Interoperability is achieved through the adoption of harmonized data standards, including widely recognized frameworks for clinical and imaging data, as well as observational datasets [9]. These standards are supported by crosswalks that align differing code systems and accommodate schema evolution to integrate new data modalities effectively. Tailored de-identification pipelines are applied to each data type, incorporating methods such as pseudonymization, k-anonymity, and calibrated noise mechanisms. These measures ensure clinical utility while minimizing the risk of re-identification. Furthermore, continuous auditing and automated compliance checks are conducted to ensure strict adherence to privacy regulations and to provide transparent reporting for regulators and stakeholders.

4.2. Cohort Discovery, Trial Allocation, and Real-World Evidence (RWE)

Cohort discovery involves the integration of both structured and unstructured clinical data, utilizing advanced natural language processing and rule-enhanced machine learning models that have been rigorously validated against manual chart reviews. This approach enhances the accuracy of eligibility inference by accounting for the complexities of phenotype heterogeneity and patterns of comorbidities, ultimately improving the precision of patient recruitment. In trial allocation, the process is designed to optimize site selection while adhering to constraints such as patient capacity, demographic diversity, logistical considerations, and regulatory timelines. Multi-objective optimization techniques are employed, incorporating fairness and stability measures to ensure that no single site or cohort is disproportionately burdened. Real-world evidence pipelines are developed to integrate data from device telemetry, insurance claims, and longitudinal patient outcomes. These pipelines are instrumental in identifying adverse events, monitoring performance metrics, and supporting the expansion of product labels. Additionally, counterfactual estimators are utilized to address confounding factors by simulating outcomes under alternative scenarios. This enables a robust evaluation of the potential impacts of trial designs or service integrations, all while maintaining a strong focus on patient safety.

4.3. Cross-Border Service Integration and Capacity Coordination

Service orchestration facilitates the integration of cross-border care pathways, ensuring patients experience a seamless combination of diagnostics, interventions, rehabilitation, and wellness services. Capacity coordination plays a critical role in optimizing resources such as bed availability, imaging equipment, and specialist schedules, while also accounting for fluctuations in tourism seasonality. Advanced scheduling algorithms are employed to address uncertainties and demand variations, enhancing operational efficiency. Referral service-level agreements and digital travel-health credentials streamline administrative processes, reducing barriers and fostering patient trust. Additionally, pricing mechanisms and bundled payment structures are designed to align healthcare provider incentives with the delivery of high-quality, continuous, and patient-centered care across different jurisdictions. These measures ensure that financial goals are balanced with clinical and operational excellence, promoting sustainable healthcare outcomes.

4.4. Incentive Design, Tokenization, and Market Mechanisms

Contribution-sensitive incentives are designed to reward stakeholders based on their measurable impact, such as marginal information gain, operational contributions, or support for trial enrollment. These incentives are often implemented through mechanisms like data tokens or credits, which can be redeemed for valuable services such as advanced analytics, prioritized access to trial slots, or financial subsidies [10]. To address challenges like free-riding, moral hazard, and adverse selection, robust mechanism designs are employed. These include audits to ensure compliance, penalty systems (commonly referred to as "slashing") for policy violations, and public leaderboards that transparently display metrics related to contribution and quality. Additionally, intellectual property and publication policies are established to clearly define joint ownership, licensing agreements, and data-sharing terms for co-developed models. These frameworks ensure fairness, protect stakeholder rights, and foster sustained collaboration within the multi-stakeholder ecosystem, promoting equitable value distribution and efficient coordination.

5. Strategy for Macao--Hengqin Regulation and Implementation

5.1. Governance and Institutional Setup

To facilitate effective cross-border collaboration in health and wellness data management, a joint Macao--Hengqin Health Data Trust has been established. This entity operates under the governance of a multi-stakeholder board that includes representatives from hospitals, contract research organizations (CROs), pharmaceutical and medical device companies, insurers, and tourism operators [11]. A dedicated technical standards committee ensures that data harmonization, interoperability, model validation, and analytics performance meet stringent clinical and operational standards. Additionally, an ethics panel is tasked with overseeing adherence to medical ethics, safeguarding patient rights, ensuring informed consent, and complying with cross-jurisdictional regulations. All analytics services must undergo rigorous pre-deployment documentation, which includes detailed model design specifications, comprehensive change logs, and thorough impact assessments. These assessments evaluate potential effects on patient safety, privacy, equity, operational efficiency, and the integration of cross-border services. A robust cross-border gateway enforces policy-as-code mechanisms, validates dynamic consent in real time, and maintains on-chain registries for all access events. This ensures full traceability, reproducibility, and auditability of data usage. Furthermore, automated alerts, escalation protocols, and oversight dashboards are implemented to enable prompt intervention in cases of high-risk or non-compliant data access, model updates, or decision outputs. These measures collectively aim to minimize systemic operational risks and enhance the reliability of cross-border health data collaboration.

5.2. Legal Harmonization and Regulatory Sandboxes

Bilateral memoranda of understanding play a crucial role in aligning frameworks for consent, secondary-use permissions, cross-border data transfers, intellectual property rights, and the admissibility of real-world evidence for regulatory purposes. Safe-harbor provisions are designed to support federated analytics and secure-enclave trials, reducing legal uncertainties and fostering collaborative innovation. Regulatory sandboxes serve as controlled environments where digital therapeutics, device telemonitoring, cross-border reimbursement mechanisms, and integrated wellness packages can be tested under carefully monitored conditions. These sandboxes operate with obligations that are scaled according to the associated risk class and are monitored using predefined clinical, operational, and safety metrics. The insights gained from these pilot programs contribute to iterative improvements in regulatory frameworks, standard-setting processes, and cross-border harmonization efforts [12, 13]. Additionally, mechanisms for dispute resolution, incident reporting, and corrective action plans are embedded within the governance structures of these sandboxes, ensuring innovation progresses while safeguarding patient safety, privacy, and public trust.

5.3. Technical Standards and Infrastructure

Shared technical standards encompass frameworks such as HL7 FHIR implementation guides for clinical data interoperability, OMOP-based research commons for observational and trial datasets, and verifiable credentials to authenticate providers, devices, and institutional identities. Advanced secure enclaves at major institutions facilitate high-sensitivity analytics through multi-party computation (MPC), ensuring privacy preservation during collaborative processes [2, 14]. Standardized pipelines for de-identification, comprehensive data provenance logs, and automated compliance checks are integral to safe data sharing and reproducibility. Observability systems are employed to monitor critical aspects such as data lineage, privacy budgets, model drift, and overall system health. Rigorous red-team exercises are conducted to simulate potential vulnerabilities, including re-identification risks, prompt injection scenarios, and adversarial attacks, thereby enhancing system resilience. Continuous integration and deployment pipelines rigorously validate model updates against metrics for robustness, fairness, and regulatory compliance before implementation. Performance dashboards provide real-time tracking of predictive accuracy, operational key performance indicators (KPIs), and allocative efficiency, ensuring optimal system functionality and accountability.

5.4. Incentives, Procurement, and Public--Private Partnerships (PPPs)

Contribution-sensitive incentive mechanisms are designed to allocate credits that can be redeemed for compute resources, priority trial access, or advantages in procurement scoring [15, 16]. These mechanisms reward stakeholders proportionally based on their marginal contributions to information gain, facilitation of trials, or operational impact. Outcome-based procurement models align payments for devices, digital therapeutics, and wellness services with measurable outcomes such as patient-reported metrics, utilization rates, adherence levels, and service quality across borders. Public-private partnerships play a crucial role in establishing shared registries, imaging hubs, rehabilitation centers, and wellness infrastructure that spans multiple regions. These partnerships are governed by transparent revenue-sharing formulas, risk-pooling strategies, and joint investment agreements. Robust governance structures ensure accountability through transparent reporting, regular audits, and compliance dashboards, aligning financial and operational incentives with broader objectives in clinical care, public health, and patient-centered outcomes.

5.5. Capacity Building and Talent Exchange

Fellowships, joint laboratories, and certification programs are strategically funded to cultivate expertise in critical areas such as clinical informatics, biostatistics, regulatory science, privacy-preserving analytics, and cross-border compliance [1]. To ensure workforce proficiency, standardized curricula and advanced digital learning platforms are implemented, focusing on federated analytics, distributed model governance, privacy safeguards, and effective multi-stakeholder coordination. Rotational programs across diverse sectors, including hospitals, contract research organizations, manufacturers, insurers, and tourism operators, are designed to facilitate comprehensive knowledge transfer, operational standardization, and the seamless adoption of collaborative workflows. Additionally, mentorship programs, interdisciplinary workshops, and cross-sector hackathons are organized to foster continuous learning, drive innovation, and enhance problem-solving capabilities. Collectively, these initiatives aim to develop an integrated and highly skilled workforce capable of sustaining collaborative, data-driven health and wellness ecosystems across Macao and Hengqin. This approach supports long-term system resilience, equitable access to services, and the delivery of high-quality healthcare solutions.

6. Conclusion

This paper outlines a comprehensive framework for fostering Macao--Hengqin collaboration in the Big Health industry, emphasizing the integration of privacy-preserving data-sharing mechanisms with the coordinated optimization of research and development, clinical operations, and service delivery. By leveraging a layered architecture, clearly defined outcome metrics, and a strategic portfolio tailored to the region's unique needs, the proposed approach demonstrates how federated and tokenized collaboration can significantly enhance efficiency. This includes compressing development timelines, improving capacity utilization, and expanding the export of high-value services, all while adhering to stringent privacy and compliance standards. The findings from a calibrated semi-synthetic evaluation suggest that while there may be marginal reductions in centralized accuracy, these are outweighed by improvements in generalization, recruitment efficiency, and regulatory alignment, ultimately driving net productivity gains. Future research should delve deeper into modeling patient and provider behaviors under cross-border incentive structures, explore the integration of cross-currency payment systems and reimbursement mechanisms, and conduct field pilots to refine incentive models and privacy budgets in alignment with real-world operational constraints. These efforts will be critical in ensuring the scalability and sustainability of the proposed framework, paving the way for transformative advancements in cross-border healthcare collaboration.

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