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A Systems-Based Approach to Digital Twin Implementation in Cardiovascular Care

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Abstract

Digital Twin (DT) technology has the potential to transform cardiac care by simulating patient-specific physiological conditions to inform clinical decisions. Despite its promise, real-world implementation of digital twins in cardiology faces challenges related to required knowledge, integration, equity, and scalability. This study proposes a lean Six Sigma-based framework to design and deploy an equitable, clinically useful digital twin for making high-stakes cardiovascular decisions, such as choosing between percutaneous coronary intervention (PCI) and coronary artery bypass grafting (CABG). Using the DMAIC framework, we start by defining a relevant clinical use case and mapping stakeholders through SIPOC and Voice of the Customer (VOC) tools. In the Measure and Analyze phases, patient-level data (e.g., age, race, clinical indicators, outcomes) will be collected and stratified to identify disparities and inefficiencies across treatment pathways. Predictive modeling and root cause analysis (e.g., fishbone diagrams, 5 Whys) will help identify factors driving variation. During the Improve phase, a digital twin prototype will be developed to simulate individual risks and outcomes using real-world data. The Control phase will focus on deploying the digital twin in clinical settings through pilot testing, statistical process control, and equity assessments to ensure long-term reliability and fairness. This approach promotes the creation of transparent, inclusive, and clinically relevant digital twins. Equity metrics will be embedded throughout to benefit underserved populations. The framework illustrates how industrial engineering principles can accelerate digital twin adoption in cardiology, fostering personalized, equitable, and scalable solutions for real-world clinical impact.

Keywords
Digital Twin, Lean Six Sigma, Cardiology, Health Equity, Healthcare Systems Engineering

1. Introduction
Digital Twin (DT) technologies hold considerable promise in cardiology, offering the capability to simulate patient-specific physiological states, predict disease progression, and evaluate treatment strategies prior to clinical implementation (Saratkar et al., 2025). Despite these advances, the integration of DTs into routine clinical cardiology remains limited. Current applications are largely restricted to research environments and face substantial challenges,

including complexities in data acquisition and integration, concerns regarding data privacy and security, variable data quality and accuracy, and the need to address algorithmic bias and fairness. Furthermore, effectively modeling human physiology and behavior remains a significant hurdle, given the dynamic and interconnected nature of these systems. The availability of adequate computational infrastructure also plays a critical role in determining feasibility (Katsoulakis et al., 2024).
A primary barrier to broader adoption is the absence of comprehensive operational frameworks that bridge technological innovation with the complexities of clinical practice. Many DT models inadequately account for the variability of clinical workflows, the necessity of clinician trust, and the imperative to integrate health equity considerations. Without deliberate attention to these factors, existing disparities in cardiovascular care, such as differential access to advanced diagnostics and therapies based on race, socioeconomic status, or geographic location, may be perpetuated or exacerbated by DT deployment.

Addressing these challenges requires a systems-engineering approach that ensures both technical rigor and practical applicability within clinical settings. Lean Six Sigma offers a well-established methodology to support such integration, enabling the systematic identification of clinical needs, measurement of performance metrics, detection of inefficiencies, optimization of workflows, and assurance of long-term reliability. Incorporating such frameworks may be critical to the equitable, sustainable, and effective implementation of digital twin technologies in cardiology.

1.1 Objectives

The objective of this work is to present an equity-aware, Lean Six Sigma-driven framework for Digital Twin deployment in cardiac care. This framework integrates evidence-based decision support with fairness safeguards and operational discipline, aiming to accelerate translation from research into impactful, real-world clinical practice.

2. Literature Review

2.1 Digital Twins in Cardiology: Current Applications and Limitations

Digital twins (DTs) in cardiology aim to create virtual, patient-specific representations by integrating mechanistic modeling with data-driven approaches to enhance diagnosis, inform treatment planning, and improve outcome prediction (Corral-Acero et al., 2020a). Early clinical applications illustrate the diversity of DT methodologies and their varying levels of technological maturity. For instance, Cardio Twin - an AI-enabled electrocardiogram (ECG) analysis platform, has demonstrated high accuracy in detecting ischemic heart disease using edge computing on mobile devices, enabling rapid and scalable deployment (Martinez-Velazquez et al., 2019). Broader reviews of the cardiovascular DT ecosystem have highlighted modalities spanning imaging, ECG, omics, and wearable sensors; however, most remain in exploratory or proof-of-concept stages (Coorey et al., 2022).

On the translational front, development roadmaps increasingly emphasize the integration of mechanistic physiological models with advances in scientific computing, artificial intelligence (AI), and sensor technologies. These integrated DT systems aim to forecast cardiovascular health trajectories and guide clinical decision-making (Sel et al., 2024a). Several personalized modeling studies underscore the potential of DTs to capture patient heterogeneity. Examples include hemodynamic twins generated from echocardiographic and ECG data, optimized using particle swarm algorithms (Mazumder et al., 2024), and "virtual pacing" simulations used to prospectively predict patient-specific responses to cardiac resynchronization therapy (CRT) (Koopsen et al., 2024). In parallel, multi-scale computational models have emerged to link molecular, cellular, and organ-level processes; however, the majority of these frameworks remain in preclinical or pre-deployment phases (Niederer et al., 2019).

Despite these advancements, several systemic barriers continue to impede real-world implementation. Key challenges include the acquisition and integration of heterogeneous data sources, ensuring data privacy and security, and maintaining high standards for data quality and accuracy. Further concerns relate to algorithmic bias and fairness, the complexity of faithfully modeling human physiology and behavior, and the need for robust computational infrastructure to support real-time and scalable deployment (Corral-Acero et al., 2020b; Sel et al., 2024b).

2.2 Equity Issues in Cardiovascular Care

Cardiovascular care remains deeply affected by entrenched inequities across race, ethnicity, gender, socioeconomic status, and geography, inequities that influence prevention, access to advanced therapies, clinical trial participation, and overall health outcomes (Addison et al., 2023a). Emerging research has begun to systematically map these disparities and their underlying causes. For instance, a recent cardio-oncology equity statement identifies multilevel barriers, including structural racism, adverse social determinants of health, and underrepresentation within the healthcare workforce, and outlines a coordinated roadmap for research and clinical intervention (Addison et al., 2023b). Similarly, investigations into heart failure have revealed a disproportionate burden among racial and ethnic minority populations, with persistent disparities across primary prevention, use of guideline-directed medical therapy, and access to advanced interventions. These disparities are attributed to a combination of unequal exposure to risk factors, limited access to care, underrepresentation in clinical research, and implicit clinician bias (Lopez et al., 2023). At the population level, data continue to demonstrate elevated cardiac mortality among African American patients, poorer outcomes in rural communities, and the ongoing under-enrollment of minority populations in cardio-oncology clinical trials, further underscoring the structural and systemic nature of inequities in cardiovascular health outcomes (Ahmad et al., 2022). Taken together, these findings reaffirm that equity is not a peripheral issue but a central determinant of cardiovascular health - demanding focused, sustained, and systemic solutions across clinical, research, and policy domains.

2.3 Lean Six Sigma in Healthcare

Lean Six Sigma (LSS) is a structured process improvement methodology designed to enhance value delivery by improving quality and speed while minimizing waste, variability, and cost. Originally developed in manufacturing and service industries, LSS has gained significant traction in healthcare since the early 2000s as a means to improve organizational performance and patient outcomes. By reducing non-value-added activities and reinforcing value-generating processes, LSS has been shown to decrease waiting times, improve patient safety, streamline clinical workflows, and increase patient satisfaction. In healthcare settings, LSS is commonly operationalized through five core domains: continuous quality improvement, Six Sigma practices, Lean management principles, patient safety, and interdisciplinary teamwork (Ahmed & Abd Manaf, 2018).

Within cardiology, LSS has been effectively employed to optimize clinical operations and enhance care delivery. For example, its application to multidisciplinary "Heart Team" meetings has improved decision-making quality and efficiency through structured agendas, balanced scheduling, and standardized communication workflows (Hoefsmit et al., 2023). In acute myocardial infarction (AMI) care, LSS-guided process redesigns have reduced door-to-treatment times by 35% and halved 30-day mortality rates (Rosa et al., 2023). Similarly, the implementation of standardized electronic referral pathways coupled with targeted staff education increased post-percutaneous coronary intervention (PCI) cardiac rehabilitation referral rates from 51% to 87%, while eliminating demographic disparities in access (Whitler et al., 2024). These examples illustrate that LSS, when embedded within clinical practice, can not only improve operational efficiency but also yield measurable gains in survival and equity.

Despite its demonstrated impact, LSS has rarely been integrated with digital twin (DT) development or equity frameworks in cardiology, a gap that represents a significant opportunity. A unified approach could leverage the complementary strengths of each domain by: (1) designing DTs through hybrid mechanistic and data-driven modeling for enhanced clinical decision-making; (2) embedding equity metrics throughout the DT lifecycle to proactively identify and mitigate disparities; and (3) applying the Lean Six Sigma DMAIC (Define, Measure, Analyze, Improve, Control) framework to ensure the operational reliability, scalability, and sustainability of DT-enabled interventions. This convergence has the potential to advance a new generation of cardiovascular care models that are not only intelligent and precise but also equitable and systemically integrated.

3. Methods

This study uses the decision between percutaneous coronary intervention (PCI) and coronary artery bypass grafting (CABG) in patients with multivessel coronary artery disease as the illustrative case for the proposed Digital Twin framework. Treatment selection in this context is shaped by a wide range of factors, including anatomical and physiological indicators, genetic predispositions, coexisting comorbidities, behavioral risks such as smoking and adherence to therapy, as well as structural and environmental determinants such as insurance coverage, hospital resources, and access to specialized care.

As Boden and Mancini (2016) note, the choice between PCI and CABG represents one of the most challenging areas in cardiovascular medicine, requiring the integration of diverse clinical and non-clinical factors. While clinical guidelines generally indicate that CABG provides superior long-term outcomes, particularly in reducing cardiac death and myocardial infarction in patients with complex multivessel disease and diabetes, PCI continues to be frequently selected in practice. This highlights a gap between evidence-based recommendations and real-world treatment patterns (Boden and Mancini 2016). Equity concerns add further complexity to this decision. Studies have documented

disparities in access to revascularization, with outcomes differing by race and socioeconomic status. For instance, Jaiswal et al.'s meta-analysis of 220,984 post-MI patients reported that Black patients, despite younger age and greater comorbidity burden, had higher all-cause mortality and stroke risk, and were less likely to undergo CABG or PCI compared with White patients. Although short-term mortality was comparable, persistent differences in treatment access and long-term outcomes underscore entrenched inequities in cardiovascular care (Jaiswal et al. 2023).
Together, these considerations establish the PCI-CABG decision as both clinically meaningful and equity-relevant, providing a suitable case to demonstrate how a Digital Twin framework can integrate individualized modeling with process improvement.

3.1 Define Phase

To illustrate the utility of the proposed framework, the Define Phase applies selected Lean Six Sigma tools to the PCI-CABG decision pathway. This phase generates three key deliverables: (1) a structured process map using SIPOC (Suppliers, Inputs, Process, Outputs, Customers) to delineate the decision pathway and its stakeholders, (2) systematic capture of stakeholder priorities through Voice of the Customer (VOC), and (3) translation of these priorities into Critical-to-Quality requirements (CTQs) to provide a structured, stakeholder-informed definition of the PCI-CABG decision problem. However, it should be noted that the Define Phase is not limited to these tools; they are presented as illustrative examples. To better structure the PCI-CABG decision pathway, a SIPOC analysis was conducted, as illustrated in Figure 1. The diagram highlights how diverse inputs, including clinical data, patient factors, and institutional resources, are transformed through diagnostic evaluation, multidisciplinary review, and shared decision-making into outputs such as treatment choice, care planning, and system-level resource allocation. By explicitly mapping these elements, the SIPOC clarifies the range of stakeholders and processes that shape this high-stakes decision. This step is important because it establishes a systems-level view of the problem, ensuring that the proposed Digital Twin framework is grounded not only in clinical data but also in organizational and equity considerations. It should be noted that the figure presents a limited set of illustrative examples; in practice, a real-world project would likely require a more extensive and detailed list for each category.

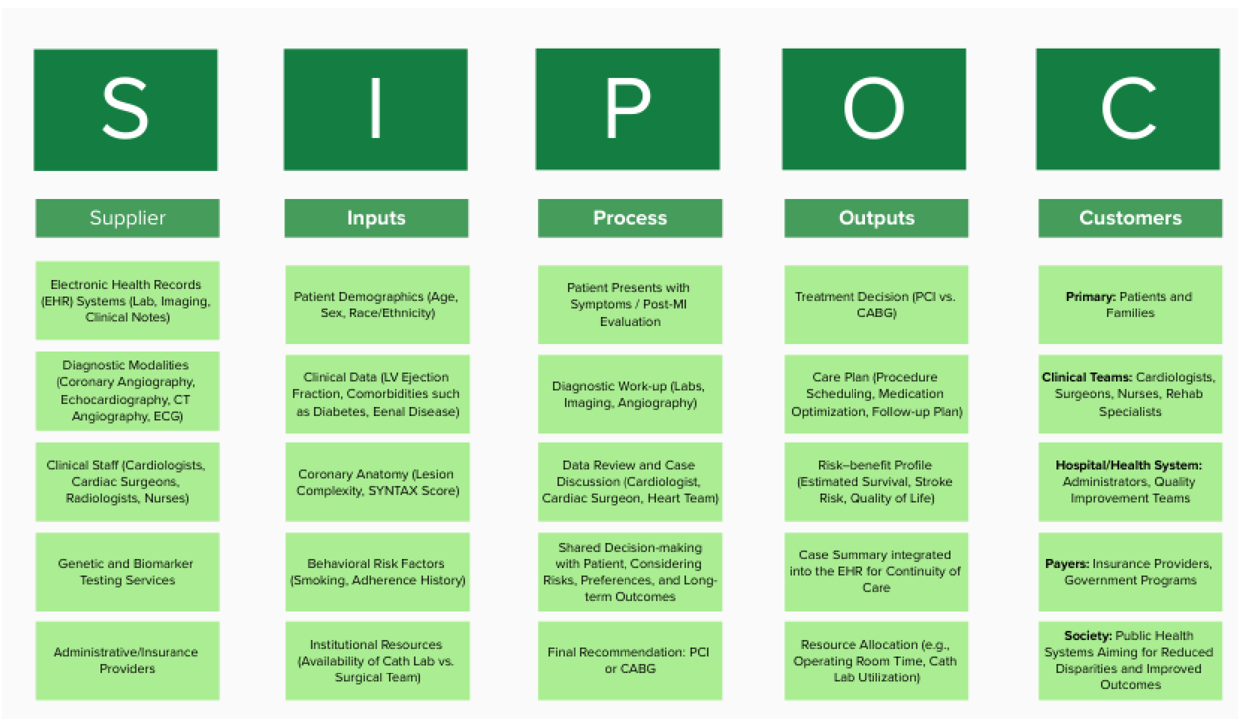

Figure 1. SIPOC diagram of the PCI-CABG decision pathway, mapping suppliers, inputs, processes, outputs, and customers to highlight the system-level factors and stakeholders influencing treatment selection and care planning

Following the mapping of the PCI-CABG decision pathway using a SIPOC (Suppliers, Inputs, Process, Outputs, Customers) diagram, the Define phase of the Lean Six Sigma (LSS) DMAIC framework applies the Voice of the

Customer (VOC) to systematically capture stakeholder expectations regarding high-quality decision-making. This step is essential for aligning process improvement efforts with the needs and values of key constituencies. Patients often prioritize clear communication, perceived fairness, and meaningful involvement in the decision process. Clinicians emphasize the importance of timely, accurate decision support tools that enhance, rather than override, clinical judgment. Administrators tend to focus on operational efficiency, adherence to evidence-based guidelines, and consistency across care teams. Meanwhile, payers are primarily concerned with cost-effectiveness, transparent documentation, and alignment with value-based care objectives. Together, these diverse perspectives inform the critical-to-quality (CTQ) requirements that shape subsequent phases of improvement.

These stakeholder perspectives are systematically translated into Critical-to-Quality (CTQ) requirements, measurable characteristics that define the success of the digital twin (DT) in supporting PCI-CABG decision-making. For patients, CTQs prioritize interpretability, ensuring that model outputs can be communicated in plain, accessible language, and equity, guaranteeing consistent performance across diverse demographic subgroups. For clinicians, CTQs emphasize predictive accuracy, with model error rates maintained within clinically acceptable thresholds; timeliness, ensuring outputs are delivered within the clinical decision-making window; and workflow integration, allowing seamless incorporation into existing electronic health records and care protocols. For administrators, CTQs focus on guideline adherence, specifically alignment with ACC/AHA recommendations, and reduction in care variation, promoting greater consistency across patient cases. For payers, CTQs center on transparent documentation, including clear traceability of how recommendations are generated, and cost-effectiveness, demonstrating economic value relative to current standards of care.

By establishing CTQs in this structured manner, diverse stakeholder expectations are converted into operational performance indicators. These can then be measured, monitored, and refined throughout the DMAIC (Define, Measure, Analyze, Improve, Control) cycle, ensuring that the digital twin not only meets technical benchmarks but also delivers value across the clinical ecosystem.

3.2 Measure Phase

The Measure Phase is designed to assemble and evaluate the data required to construct the digital twin and to characterize how PCI-CABG decisions would be assessed in practice. Data collection in this framework would draw from multiple domains. Clinical variables would encompass demographics, cardiovascular risk factors, diagnostic imaging, functional testing, laboratory measures, treatment history, and outcomes such as complications, readmissions, and survival. Social determinants would be integrated to capture broader influences on care, including socioeconomic status, insurance coverage, transportation, and neighborhood-level indices. Process metrics, such as time from presentation to angiography and from diagnostic results to intervention, would be incorporated to identify delays and inefficiencies.

A structured overview with additional data types and examples is provided in Figure 2. Data quality checks are proposed to confirm that all relevant variables are captured without missing values, that patient subgroups (e.g., by age, sex, race/ethnicity, and socioeconomic status) are adequately represented, and that systematic biases, such as differences in test ordering, treatment allocation, or follow-up reporting, can be detected. These steps are critical to ensure that the dataset provides a reliable and unbiased foundation for subsequent modeling.
By combining high-resolution clinical data with structural determinants of access, the Measure Phase establishes an equity-aware dataset that forms the foundation for accurate and fair DT modeling. This structured base enables the subsequent Analyze Phase, where methods would be applied to uncover sources of variation, inefficiency, and inequity.

3.3 Analyze Phase

The Analyze Phase in this framework focuses on understanding why variation and inequities arise in the PCI-CABG decision process and on identifying where a digital twin could intervene. This step generates three key deliverables: (1) candidate methods to quantify outcome drivers, (2) structured tools to identify system-level root causes, and (3) an equity lens to highlight subgroup differences.

First, statistical methods that could be applied include logistic regression to estimate the probability of binary outcomes, such as the likelihood of hospital readmission; survival analysis to examine time-to-event outcomes, like the time until heart failure hospitalization; and machine learning techniques such as random forest or gradient boosting to explore which combinations of clinical and social variables are most predictive of adverse events. Propensity score matching can also be considered to compare outcomes of PCI and CABG fairly when controlling for baseline patient characteristics. Second, root cause analysis tools such as fishbone diagrams, the 5 Whys technique, and Failure Modes and Effects Analysis (FMEA) provide structured ways to trace why gaps persist between guidelines and real-world practice. Process mapping supports this by clarifying clinical decision points, the information currently used by providers, and where variability or delays occur in the workflow. Finally, equity-focused analysis can be incorporated by stratifying these findings across race, income, insurance, and geography. This makes it possible to highlight, for example, whether certain groups experience longer delays, fewer referrals, or limited access to advanced interventions. By combining these tools, the Analyze Phase builds a foundation for the DT to target not only clinical accuracy but also systemic inefficiencies and inequities in cardiovascular care. The insights generated from these candidate analytical and root cause methods should guide the Improve Phase, which focuses on model design, fairness safeguards, and usability planning.

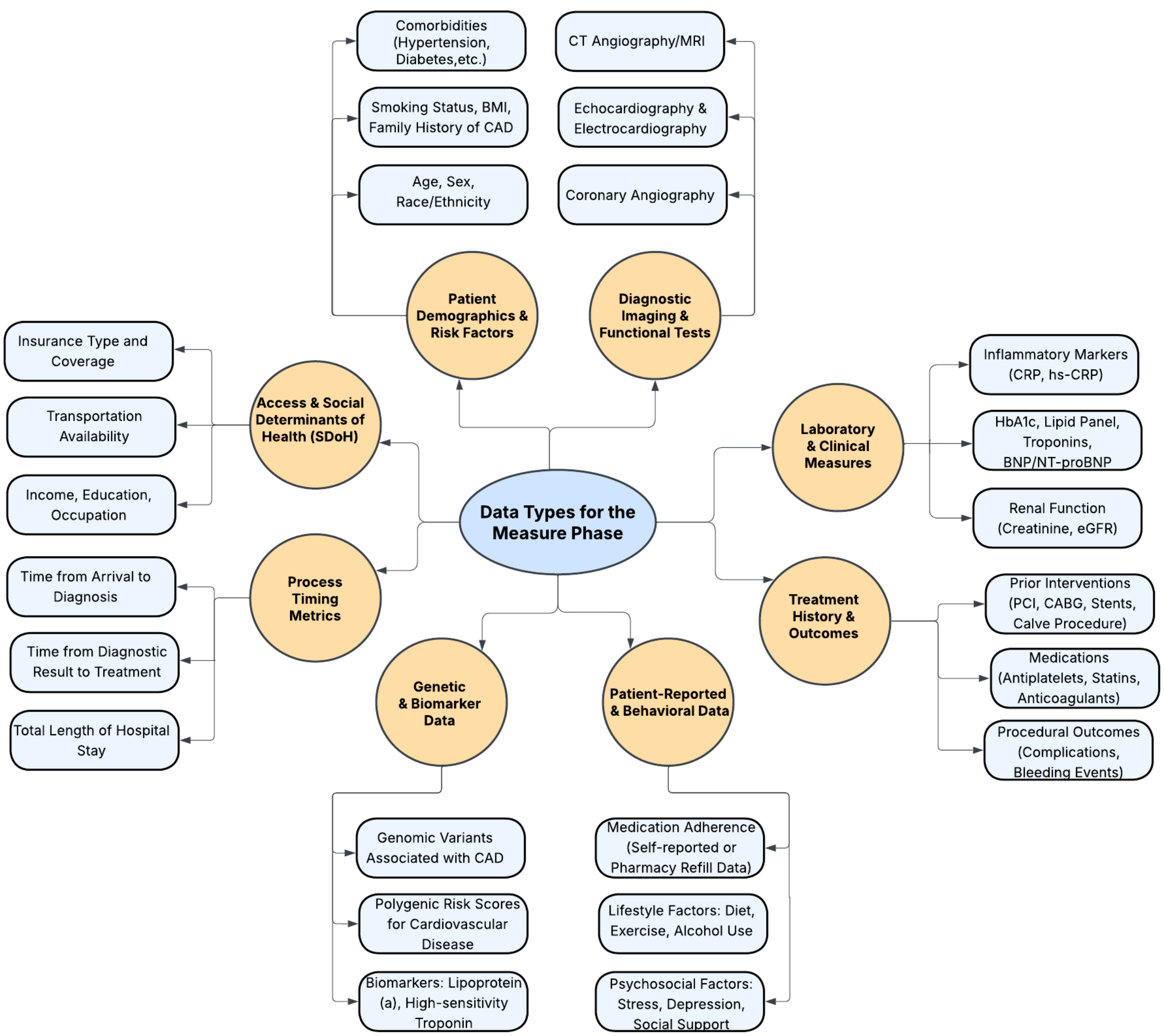

Figure 2. Data types for the Measure Phase, illustrating the integration of clinical, imaging, laboratory, treatment history, genetic, behavioral, social, and process-related domains to support equity-aware Digital Twin development for PCI-CABG decision-making

3.4 Improve Phase

The Improve phase does not aim to build a fully operational clinical system but rather to define the critical steps necessary to ensure that the digital twin (DT) model is accurate, fair, and usable in real-world settings. This phase yields three primary deliverables: (1) a robust model design, (2) safeguards to promote fairness, and (3) an approach for usability testing and clinical feedback integration.

First, the model design involves the development of a patient-specific simulation that integrates clinical, imaging, and social determinants of health data to generate individualized outcome predictions or treatment recommendations. Second, fairness safeguards are introduced to evaluate model performance across racial, gender, and socioeconomic subgroups. If disparities are identified, appropriate mitigation strategies, such as algorithmic adjustments or retraining with more representative data, can be proposed to ensure equitable performance. Third, simulation-based testing is used to examine the model's behavior in hypothetical scenarios before clinical deployment. This step assesses whether the DT provides timely, consistent, and actionable guidance and whether it reduces practice variation compared to current standards.

In parallel, attention is given to interface design and usability. This includes conceptualizing clinical dashboards or alert systems that align with existing workflows and minimize cognitive burden for end users. Usability testing would incorporate feedback from key stakeholders, including cardiologists, cardiothoracic surgeons, and administrators, to refine the interface, outputs, and integration points before implementation.
By structuring the Improve phase in this manner, the framework clarifies how a digital twin can progress from a theoretical model to a practical, equitable clinical tool. Once the model has been optimized for accuracy, fairness, and usability, the Control phase focuses on strategies for ongoing monitoring, auditing, and sustaining performance in routine clinical practice.

3.5 Control Phase

The purpose of the Control Phase is to define the structures that would ensure performance, safety, and equity over time. This phase should produce four main deliverables: (1) a pilot deployment plan, (2) systems for ongoing monitoring, (3) equity and feedback mechanisms, and (4) a long-term sustainability roadmap.
First, a pilot launch could be envisioned in a single hospital unit like a cardiology ward or heart failure clinic, where clinicians use the Digital Twin in parallel with normal decision-making under supervision. Second, ongoing monitoring systems would be necessary to track accuracy, response times, safety outcomes, and how often clinicians follow or override the tool. Statistical Process Control (SPC) charts are one example of how such monitoring could be organized. Third, equity audits and feedback loops would be applied regularly to check whether predictions remain consistent across subgroups (e.g., race, gender, or insurance status), while allowing clinicians and nurses to report issues and suggest refinements. Finally, a sustainability and scaling plan would ensure continuity: hospital staff could be trained to manage the system, Standard Operating Procedures (SOPs) could be developed for troubleshooting, and pathways for scaling to other sites, conditions, or patient groups could be proposed. This framework makes clear how a Digital Twin could theoretically move from pilot testing to reliable, equitable, and sustainable integration into healthcare systems. By concluding with a sustainability roadmap, the Control Phase ensures that the proposed framework is not only robust but also equipped for long-term integration into healthcare systems.

4. Results and Discussion

Although the proposed framework is theoretical and initially narrow in scope, focusing on improving the selection between PCI and CABG, it discusses several meaningful expected outcomes. These outcomes vary depending on how each phase of the framework is applied within an institution. For example, during the Define Phase, one institution may focus on improving access for patients from rural areas, where transportation barriers and limited insurance coverage contribute to worse outcomes. Another institution may use the same framework to prioritize risk stratification across different patient categories, tailoring decision support to their population. Similarly, the Measure Phase outcomes depend on the quality and design of the data collection process, including how comprehensively, accurately, and consistently data are captured, stored, and prepared for analysis. The Analyze Phase would reveal which clinical and structural factors most strongly drive variation, providing either feedback to improve measurement practices or guidance for the Improve Phase. During Improve, expected outcomes hinge on the success of Digital Twin design, whether implemented for outcome prediction, risk stratification, or patient-centered decision support. Finally, in the Control Phase, outcomes would reflect the degree of stakeholder engagement, the responsiveness of clinicians to feedback, and the ability to demonstrate early improvements in patient outcomes.

From this sequence, several specific expected outcomes emerge:

1. Enhanced treatment selection between PCI and CABG, integrating multiple clinical, social, and equity factors to support more patient-centered decisions.
2. Better data collection practices, characterized as comprehensive, multidimensional, coordinated, and consistently documented in structured formats.
3. Improved resource allocation, enabling hospitals to better match procedural and staffing resources to patient needs.
4. Evidence-based patient stratification, reducing the likelihood of avoidable complications and future cardiovascular events.
5. Replication of the human heart *in silico*, customized to patient-level lab results and clinical information.
6. Improved understanding of patient demographics and equity drivers, such as rural vs. urban residence, insurance status, referral pathways, and speed of care delivery in urgent cases.

The range of outcomes demonstrates the framework's potential to influence not only clinical decisions but also data infrastructure, health equity, and systems performance. Importantly, these outcomes align with the Institute of Medicine's six aims for healthcare improvement, advancing care that is safe, timely, effective, equitable, patient-centered, and efficient (Committee on Quality of Health Care in America 2001).
It is important to emphasize that industrial and systems engineering (ISE) methods hold significant potential to advance improvements in cardiology. The PCI-CABG case was presented here as an illustrative example to demonstrate the framework in practice, but the applications are far broader, as shown in Table 1, which outlines several additional clinical problems where DTs could be applied. These examples indicate that the framework is not confined to a single condition but can be adapted to diverse challenges across cardiovascular care. More broadly, Design for Six Sigma provides the umbrella under which such applications can be structured. Each phase of the DMAIC cycle is deliberately structured to ensure the framework follows a systematic, evidence-based methodology. With its wide range of tools embedded in each phase, Lean Six Sigma offers the flexibility and rigor to drive meaningful, sustainable change across multiple dimensions of cardiovascular healthcare.

Table 1. Examples of clinical problems in cardiology where Digital Twin applications could be applied, illustrating the broader potential of Lean Six Sigma–guided frameworks beyond the PCI-CABG case

Clinical Problem	Description	Why It Fits for DT
Heart Failure Readmission Risk	Identifying which discharged patients are at high risk of coming back within 30 days	DT can simulate patient-specific recovery trajectories
Triage of Chest Pain in the ED	Distinguishing low-risk vs. high-risk patients with chest pain (ruling out MI safely)	DT can integrate ECGs, labs, and history for real-time decision support
Timing of Intervention for Aortic Stenosis	Deciding when a patient with moderate-to-severe aortic stenosis should undergo Transcatheter Aortic Valve Replacement (TAVR)	DT can model valve function deterioration and risk prediction
Medication Selection in AFib	Choosing the optimal anticoagulant based on risk of stroke vs. bleeding	DT can integrate renal function, age, and bleeding history

While the proposed framework highlights the potential of combining Digital Twins, equity considerations, and Lean Six Sigma in cardiology, several limitations must be acknowledged. First, the framework is conceptual and does not yet include empirical testing, meaning the expected outcomes remain theoretical. Second, implementation challenges such as data availability, the effort and time required for data collection and design, interoperability across hospital systems, and compliance with data privacy regulations may constrain real-world application. Third, the complexity of modeling human physiology and behavior introduces technical uncertainties, particularly when integrating multi-scale clinical and social data, which necessitates strong interdisciplinary collaboration. In addition, successful adoption will rely heavily on stakeholder engagement and the cultural readiness of healthcare organizations, both of which can vary considerably. Practical challenges must also be addressed, including staff training, continuous monitoring, and technical refinements to ensure that the system is usable in busy clinical environments. For instance, clinicians may not have the time to interpret detailed risk scores during routine workflow; therefore, the DT should be designed with user-friendly features such as automated alerts, dashboards, or visual warning signals that can quickly flag concerns for clinicians and quality teams. Addressing these issues requires structured training programs, clear written protocols, and iterative monitoring to maintain trust and reliability.

Moving forward, the framework should be advanced through phased implementation in real-world settings. Initial pilot studies in cardiology units could provide valuable insight into feasibility, workflow fit, and user adoption, while also generating feedback for iterative refinement. Establishing structured training modules and practical guides for clinicians, nurses, and administrators will be essential to promote consistent usage and confidence in the system. On the technical side, developing user-friendly features such as dashboards, automated alerts, and built-in equity checks should be prioritized to support decision-making in fast-paced environments. Strong interdisciplinary collaboration, linking engineers, clinicians, data experts, and policymakers, will be needed to manage modeling complexity and regulatory challenges around privacy and interoperability. Over time, the approach can expand beyond PCI-CABG to additional cardiology contexts, such as heart failure care or valve interventions, illustrating the broader capability of Lean Six Sigma-driven Digital Twin applications to foster sustainable improvements in healthcare.

5. Conclusion

This paper proposes a Lean Six Sigma-driven, equity-aware Digital Twin (DT) framework for cardiology and illustrates its use on the PCI-CABG decision. By structuring the work through DMAIC, the method translates stakeholder needs (VOC) into CTQs in the Define phase, builds an equity-aware data foundation in the Measure phase, specifies candidate analytical and root-cause tools in the Analyze phase, outlines a patient-specific DT with fairness safeguards and usability pathways in the Improve phase, and defines monitoring, audit, and sustainability mechanisms in the Control phase. In doing so, the framework shows how industrial and systems engineering principles can accelerate DT implementation in cardiology, aligning personalized modeling with operational reliability and equitable care.

Although theoretical, the framework yields clear, phase-specific deliverables and expected outcomes: more consistent PCI-CABG selection, improved data practices, evidence-based patient stratification, better resource allocation, and routine equity monitoring. It directly targets known barriers in the DT literature, such as data integration, trust, usability, and deployment, and leverages proven process-improvement discipline to bridge research prototypes to scalable, real-world clinical impact. The approach is generalizable beyond PCI-CABG and provides a practical guideline for piloting, iterative refinement, and future expansion to other cardiovascular decisions.

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