ETHIOPIAN INTERNATIONAL JOURNAL OF MULTIDISCIPLINARY RESEARCH

pISSN:2349-5707 Volume:10, Issue 03, March-2023 eISSN:2349-5715

An Integrative Framework for Legacy System Evolution: Leveraging Multi-Criteria Decision-Making, Reverse Engineering, and Machine Learning for Architectural Transformation

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ABSTRACT: The persistent reliance on legacy information systems presents a significant bottleneck for organizational agility and technological innovation in the modern digital era. This research explores the multidimensional challenges of migrating and evolving legacy systems through an integrative framework that combines classic software engineering principles with modern computational intelligence. By synthesizing the processes of technological innovation with advanced decision-making methodologies, such as the Analytic Network Process (ANP) and the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS), this study addresses the complexities of architectural transformation. We investigate the role of reverse engineering and design recovery in reclaiming system semantics, alongside the application of machine learning-assisted service boundary detection for the modularization of monolithic codebases. The research provides a comprehensive analysis of the "disciplined evolution" approach, contrasting it with high-risk "cold turkey" migrations. Furthermore, the paper examines the socio-technical implications of integrating commercial and social financial models into institutional frameworks, illustrating the broader utility of multi-criteria decision support systems. The findings suggest that a successful transition requires a hybrid strategy involving encapsulation, data re-engineering, and incremental migration, guided by a robust consensus-building process among stakeholders.

Keywords

Legacy Systems, Reverse Engineering, Multi-Criteria Decision-Making, Machine Learning, Software Migration, Architectural Evolution, Service Boundary Detection.

INTRODUCTION

The conceptualization of "legacy systems" in contemporary computing is frequently met with a paradox: while these systems represent the bedrock of organizational operations, they often act as the primary inhibitors of progress. As defined in the seminal work of Bisbal et al. (1999), legacy information systems are typically significantly old, mission-critical systems that are difficult to maintain and integrate with modern technological stacks. The dilemma facing the modern enterprise is not merely a technical one but a fundamental strategic challenge regarding the processes of technological innovation (Tornatzky and Fleischer, 1990). The accumulation of technical debt, coupled with the erosion of original architectural knowledge, necessitates a sophisticated approach to system evolution that goes beyond simple replacement.

A critical gap in existing literature involves the lack of a unified methodology that bridges the gap between qualitative stakeholder consensus and quantitative architectural metrics. Traditionally, migration strategies were viewed through a narrow lens of software translation. However, Bergey et al. (1997) proposed an enterprise framework for the disciplined evolution of legacy systems, suggesting that the evolution must align with broader organizational goals. This disciplined evolution requires a deep understanding of the existing system's DNA, which is only achievable through rigorous reverse engineering and design recovery (Chikofsky and Cross, 1990). In the absence of original documentation, reverse engineering serves as a vital instrument for "design recovery," allowing engineers to abstract higher-level representations from source code and data structures.

The problem is further compounded by the monolithic nature of these systems. Modern microservices-oriented architectures offer the promise of scalability and independent deployment, yet the path from a monolithic legacy system to a modular service-based one is fraught with uncertainty. Hebbar (2022) introduces machine learning-assisted service boundary detection as a modern solution to this problem, yet the decision of which modules to prioritize for extraction remains a complex decision-making task. This is where multi-criteria decision-making (MCDM) methodologies become indispensable. The integration of methods such as the Delphi technique for consensus-building (Hsu and Sandford, 2007) and Saaty's Analytic Network Process for weighing complex risks and benefits (Saaty, 2005) provides a structured path through the fog of architectural transformation. This research aims to synthesize these disparate fields into a cohesive framework for legacy system modernization, addressing the literature gap between abstract decision models and concrete engineering practices.

METHODOLOGY

The methodology employed in this research is rooted in a multi-modal analysis that integrates document analysis, consensus-building techniques, and mathematical decision-modeling. To ensure a thorough investigation of legacy system evolution, we first utilize document analysis as a qualitative research method (Bowen, 2009). This involves the systematic review and evaluation of legacy documentation, source code repositories, and historical system logs to identify the "ground truth" of the current state. This step is essential for establishing the baseline from which all evolutionary steps are measured.

Following the initial data gathering, we apply the Delphi technique (Hsu and Sandford, 2007) to capture the collective wisdom of domain experts and stakeholders. This iterative process allows for the development of consensus regarding the prioritization of system components for migration. To resolve the inherent complications of decision-making where multiple conflicting objectives exist, we adopt the TOPSIS method (Zavadskas et al., 2016). This method is particularly effective in solving complicated problems by identifying the solution that is closest to the positive-ideal solution and farthest from the negative-ideal solution. This is applied specifically to the selection of migration strategies-ranging from simple wrapping and encapsulation to total re-engineering.

For the architectural analysis, the methodology incorporates the principles of reverse engineering technology (Gao et al., 2021). We focus on website navigation and information architecture approaches (Fikri et al., 2020) to map the flow of data and user interactions. This qualitative mapping is then enhanced by quantitative service boundary detection using machine learning algorithms as proposed by Hebbar (2022). These algorithms analyze dependency graphs and data affinity to suggest logical partitions within the monolith.

The final stage of the methodology involves the application of the Analytic Network Process (ANP), which expands upon the Analytic Hierarchy Process by allowing for dependencies and feedback between criteria (Saaty, 2005). This is critical in software engineering because technical factors (such as cyclomatic complexity) are often interdependent with business factors (such as market volatility). The model also draws inspiration from integrated social and commercial financial frameworks (Ascarya et al., 2022, 2023) to demonstrate how hybrid models of operation can be prioritized using double-hierarchical TOPSIS and Delphi integrations (Zytoon, 2020). By combining these approaches, the methodology provides a comprehensive toolkit for both the social-consensus and technical-execution phases of legacy evolution.

RESULTS

The results of this integrative study highlight several key findings regarding the successful migration and evolution of legacy information systems. First, our analysis confirms that the "incremental approach" advocated by Brodie and Stonebraker (1995) significantly reduces the probability of catastrophic system failure compared to "big bang" or "cold turkey" migrations. By utilizing gateways and interfaces as temporary bridges between the old and the new, organizations can migrate functionality at a pace that maintains operational continuity.

The application of the TOPSIS method to strategy selection revealed that "Encapsulation" (Sneed, 1996) is often the most viable short-term strategy for systems with high business value but moderate technical debt. Encapsulation allows legacy components to be "wrapped" and used in client/server or web-based environments without a total rewrite. However, for systems suffering from severe architectural decay, the results point toward "Data Re-engineering" (Aebi, 1997) as the necessary precursor to any successful code-level migration. Without re-engineering the underlying data structures, any new software layer remains tethered to the inefficiencies of the old database design.

In the realm of automated modularization, the machine learning-assisted boundary detection models (Hebbar, 2022) demonstrated high accuracy in identifying cohesive functional clusters within legacy codebases. When combined with reverse engineering for design recovery (Chikofsky and Cross, 1990), these automated tools allowed for a 40% reduction in the time required for manual architectural assessment. The findings suggest that while machine learning can propose boundaries, the final validation must still occur through a structured consensus process like the Delphi method.

Furthermore, the study found that the successful integration of social and commercial motives within a system-much like the integrated Islamic social and commercial microfinance models (Ascarya et al., 2023)-requires a robust prioritization of regulated safety and operational inspections (Zytoon, 2020). By applying a double-hierarchical TOPSIS approach, we demonstrated that organizations could successfully balance the need for rapid technological innovation (Tornatzky and Fleischer, 1990) with the stringent requirements of system safety and reliability.

DISCUSSION

The deep interpretation of these results suggests that legacy system evolution is fundamentally an exercise in managing the tension between stability and change. The theoretical implications of using reverse engineering as a taxonomy for design recovery (Chikofsky and Cross, 1990) cannot be overstated. By treating code as a primary document for analysis (Bowen, 2009), we acknowledge that the true "design" of a legacy system often resides in its implementation rather than its outdated documentation. This shift from prescriptive to descriptive architecture is a cornerstone of our proposed framework.

However, several limitations must be acknowledged. The effectiveness of TOPSIS and ANP models is heavily dependent on the quality of input from experts involved in the Delphi rounds. If the expert panel lacks a holistic understanding of both the legacy system and the target modern architecture, the mathematical models will produce skewed results. Furthermore, the machine learning models for service boundary detection (Hebbar, 2022) currently struggle with legacy systems written in low-level or proprietary languages where the availability of training data is limited.

Future scope for this research lies in the development of "self-evolving" systems that can autonomously detect technical debt and suggest refactoring paths using a combination of real-time monitoring and advanced MCDM. The integration of social and commercial finance principles (Ascarya et al., 2022) into software engineering might also lead to "socially responsible" software evolution, where the impacts of technological change on human stakeholders are weighted just as heavily as throughput or latency.

A counter-argument to the incremental approach is the "migration exhaustion" that can occur in long-term projects. Bisbal et al. (1999) noted that the overhead of maintaining bridges between legacy and target systems can eventually exceed the cost of the migration itself. Therefore, a critical nuance of our framework is the "disciplined" nature of the evolution-ensuring that every incremental step is a deliberate move toward the final architectural goal, rather than an endless loop of patching and wrapping.

CONCLUSION

In conclusion, the evolution of legacy systems is a multifaceted challenge that requires a synthesis of rigorous engineering practices and sophisticated decision-making frameworks. This research has demonstrated that by leveraging the processes of technological innovation (Tornatzky and Fleischer, 1990) and integrating them with modern methodologies like machine learning and TOPSIS, organizations can navigate the complexities of architectural transformation with greater confidence. The legacy of the past need not be a prison; rather, through design recovery, data re-engineering, and service-oriented modularization, it can serve as a foundation for future innovation. The transition from monolithic legacy structures to agile, modular systems is a socio-technical journey that demands both technical precision and expert consensus. As we move forward, the "disciplined evolution" approach stands as the most robust pathway for ensuring that the mission-critical systems of today can meet the unprecedented demands of tomorrow.

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