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MATHEMATICAL FOUNDATIONS FOR COMPUTATIONAL COMMERCE: EMERGING TRENDS AND APPLICATIONS

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Abstract

Computational commerce a synergy of commerce and computation – is transforming how businesses operate, innovate, and compete. Underlying this transformation are powerful mathematical foundations. This article explores the critical mathematical models, algorithms, and computational theories that enable modern commerce. From linear programming and game theory to stochastic processes and machine learning, we highlight emerging trends and applications across finance, logistics, pricing, consumer behavior analysis, and digital marketplaces. The paper offers a detailed overview of recent research and practical implementations, underscoring the future trajectory of computational commerce as driven by mathematical innovation.

Keywords

Computational Commerce, Mathematical Modeling, Optimization Algorithms, Game Theory, Stochastic Processes, Dynamic Pricing, Supply Chain Optimization, Machine Learning in Commerce, Recommendation Systems, Financial Analytics, Algorithmic Trading, E-commerce Mathematics, Graph Theory, Blockchain and Crypto economics, Quantum Computing in Commerce, Explainable AI (XAI), Data-Driven Decision Making, Commercial Applications of Mathematics, Smart Commerce, Predictive Analytics.

1. Introduction

The digital economy has redefined commerce. At the heart of this evolution lies computational commerce a multidisciplinary domain integrating algorithms, data structures, optimization, economics, and artificial intelligence to support decision-making and operations in commerce. Mathematics acts as the cornerstone of this domain, enabling rigor, predictability, and innovation.

In this article, we analyze the mathematical foundations that empower computational commerce. We examine how classical and modern mathematical theories are integrated into systems for automated trading, dynamic pricing, logistics optimization, recommendation engines, and e-commerce fraud detection. Additionally, we investigate how emerging technologies like blockchain, quantum computing, and AI redefine the mathematical tools required for tomorrow's commerce.

Objective of Study

The primary objective of this study is to investigate and articulate the mathematical foundations underlying computational commerce. It aims to explore how various mathematical models, algorithms, and computational theories contribute to the effectiveness and innovation of commercial systems. Specifically, the study seeks to:

- ❖ Analyze the integration of mathematical tools in pricing, trading, supply chain optimization, and recommendation systems.
- ❖ Identify emerging mathematical trends such as quantum algorithms, explainable AI, and blockchain-based cryptographic systems.

- ❖ Highlight how businesses leverage these mathematical approaches for data-driven decision-making, personalization, and risk mitigation.
- ❖ Provide case studies to demonstrate the practical implementation and real-world impact of mathematical models in commerce.

Research Problem

In the rapidly evolving digital economy, businesses face increasing complexity in operations, competition, and consumer expectations. Traditional commerce methods are insufficient to address the high dimensionality, uncertainty, and scalability issues involved. The core research problem centers on how mathematical models and computational techniques can be effectively applied to optimize commercial decision-making and enhance system performance across various domains such as pricing, logistics, finance, and fraud detection. Furthermore, with the advent of AI and quantum computing, the study also investigates the adequacy and adaptability of current mathematical models in emerging technological contexts.

Scope of Study

This study covers a multidisciplinary examination of mathematical applications in computational commerce. The scope includes:

- ❖ **Mathematical Theories:** Optimization, probability, graph theory, game theory, and statistics.
- ❖ **Computational Techniques:** Machine learning, algorithmic trading, and simulation modeling.
- ❖ **Application Domains:** E-commerce, financial markets, supply chains, and digital platforms.
- ❖ **Technological Frontiers:** Blockchain, quantum computing, explainable AI, and digital twins.
- ❖ **Case Studies:** Real-world implementations by companies such as Amazon, Uber, and Alibaba.

The geographical focus is global, considering multinational corporations and cross-border commerce platforms. The study is theoretical and conceptual but includes empirical case analysis.

Review of Literature

Several prior works have established the foundational concepts of mathematical modeling in economics and computer science. Boyd and Vandenberghe (2004) offer comprehensive insights into convex optimization, a critical tool in machine learning and logistics. Varian (2010) presents microeconomic principles that underpin pricing and game-theoretic models in market structures. Russell and Norvig (2020) discuss artificial intelligence algorithms that integrate optimization and statistical learning, crucial for personalized commerce.

Shapiro et al. (2009) provide extensive treatment of stochastic programming, which has been effectively applied in uncertain commercial environments such as dynamic pricing and supply chain risk. Milgrom (2004) explores the real-world implications of auction theory, a subdomain of game theory pivotal to online marketplaces and advertising.

Recent developments in explainable AI, blockchain economics, and quantum optimization have been discussed in numerous journal articles and white papers, pointing to the ongoing evolution of mathematical applications in commerce. However, there remains a gap in synthesizing these contributions into a unified framework that bridges theory and practical commercial deployment—this study attempts to fill that gap.

Research Methodology

The study follows a qualitative-descriptive and analytical research methodology, with the following components:

- ❖ **Conceptual Analysis:** Theoretical exploration of mathematical domains such as optimization, game theory, and stochastic processes to explain their relevance in computational commerce.
- ❖ **Application Mapping:** Analytical review of how specific mathematical models are applied in domains like dynamic pricing, recommendation systems, fraud detection, and financial analytics.
- ❖ **Case Study Method:** Examination of real-world commercial giants Amazon, Uber, and Alibaba to understand the operationalization of mathematical models at scale. Case studies are selected for their prominence and representativeness.

- ❖ **Literature Synthesis:** Integration of key academic sources and contemporary research findings to build a comprehensive understanding of trends and challenges.
- ❖ **Exploratory Component:** Discussion of future directions including AI transparency, blockchain applications, and quantum computing from a mathematical perspective, supported by secondary data and conceptual frameworks.

The methodology is non-empirical in the sense that it does not involve primary data collection but draws on established literature, documented case studies, and theoretical modeling.

2. Mathematical Foundations of Computational Commerce

2.1 Optimization Theory

Optimization is central to many commercial applications pricing, inventory, routing, marketing, and operations. Mathematical optimization involves choosing the best element from a set of available alternatives, typically defined by constraints and objective functions.

- ❖ **Linear Programming (LP):** Applied in logistics, supply chain management, and production planning.
- ❖ **Integer Programming (IP):** Useful for resource allocation problems with discrete variables.
- ❖ **Convex Optimization:** Dominates modern machine learning models used in commerce.
- ❖ **Multi-Objective Optimization:** Balances cost, time, and customer satisfaction in decision-making.

2.2 Game Theory

Game theory models competitive and cooperative behaviors among rational agents. In commerce, it's applied to:

- ❖ Auction design (e.g., eBay bidding models)
- ❖ Pricing strategies in oligopolies

- ❖ Contract negotiations and coalition formation
- ❖ Platform competition (e.g., Uber vs. Lyft)
- ❖ Key concepts include Nash equilibrium, dominant strategies, and Pareto efficiency

2.3 Probability and Stochastic Processes

Commerce is uncertain by nature. Probability theory and stochastic modeling help in risk management, forecasting, and decision-making under uncertainty.

- ❖ Markov Chains model customer journeys or credit scoring.
- ❖ Poisson Processes help in queuing systems, like call centers or online support.
- ❖ Bayesian Statistics support demand forecasting, fraud detection, and A/B testing.

2.4 Graph Theory and Network Science

Used in Logistics, Recommendation Systems, and Supply Chain Optimization.

- ❖ Transportation Networks use shortest path algorithms.
- ❖ Social Networks facilitate viral marketing and influencer analysis.
- ❖ Graph Embeddings support personalized recommendation systems.

2.5 Machine Learning and Mathematical Statistics

ML models grounded in statistics and optimization are foundational for personalization, predictive analytics, and automation.

- ❖ Regression and Classification models customer behavior.
- ❖ Clustering segments users and products.
- ❖ Reinforcement Learning optimizes real-time decisions (e.g., ad placement).
- ❖ Time Series Forecasting predicts demand and stock trends.

3. Applications in Modern Commerce



Figure 1: E-Commerce Application Development

3.1 Dynamic Pricing and Revenue Management

Dynamic pricing uses real-time data to adjust prices based on demand, competition, and other factors.

- ❖ **Mathematical Model:** $p(t) = f(D(t), C(t), R(t))$, where D = demand, C = competition, R = real-time inputs.
- ❖ Airlines, hospitality, and e-commerce platforms use stochastic optimization and machine learning for price setting.

3.2 Supply Chain Optimization

Supply chain management relies on mathematical modeling for efficiency, cost reduction, and resilience.

- ❖ LP/IP models for inventory control
- ❖ Network flows for transportation routing
- ❖ Stochastic models for demand uncertainty

Example

Amazon's fulfillment system uses algorithms for bin packing, last-mile delivery, and route optimization.

3.3 Financial Commerce and Algorithmic Trading

Financial Markets are dominated by Quantitative Models

- ❖ Black-Scholes Model for options pricing
- ❖ Monte Carlo Simulations for risk analysis
- ❖ High-frequency trading uses statistical arbitrage and predictive modeling

3.4 Fraud Detection and Risk Analytics

Statistical learning methods and anomaly detection algorithms flag potential fraud.

- ❖ Bayesian Networks
- ❖ Hidden Markov Models
- ❖ Support Vector Machines

Used by PayPal, Mastercard, and Banks to reduce transaction risks.

3.5 Personalized Recommendation Systems

Recommenders Drive Conversion and Engagement in E-Commerce

- ❖ Matrix Factorization (Netflix Prize winner)
- ❖ Deep Learning (e.g., neural collaborative filtering)
- ❖ Graph-based recommender systems

Mathematical models optimize for accuracy, serendipity, and diversity.

4. Emerging Trends

4.1 Explainable AI (XAI) in Commerce

Transparency in algorithmic decisions is crucial in credit scoring, lending, and insurance.

- ❖ Shapley values (from game theory) provide interpretability.
- ❖ LIME, SHAP, and counterfactual explanations help regulatory compliance and trust-building.

4.2 Blockchain and Crypto Economics

Blockchain enables decentralized commerce, underpinned by cryptographic math

- ❖ Hash functions, Merkle trees
- ❖ Zero-knowledge proofs for privacy
- ❖ Game-theoretic design for consensus mechanisms

Applications

Supply chain tracking, NFTs, decentralized finance (DeFi)

4.3 Quantum Computing and Optimization

Quantum algorithms (e.g., quantum annealing) promise breakthroughs in optimization problems.

Use Cases

Portfolio Optimization, Supply Chain Routing, Fraud Detection.

4.4 Digital Twins and Simulation

Mathematical modeling creates virtual replicas of supply chains, warehouses, or customer flows.

- ❖ Agent-based modeling for customer simulations.
- ❖ Differential equations for real-time logistics adjustments.

5. Case Studies

5.1 Amazon: Optimization at Scale

Amazon's recommendation, pricing, and logistics systems are powered by robust mathematical infrastructure. Key implementations include:

- ❖ K-means and SVD for product recommendations
- ❖ Dynamic routing using Dijkstra's and A* algorithms
- ❖ Multi-echelon inventory optimization

5.2 Uber: Game Theory and Pricing

Uber uses

- ❖ Surge pricing modelled using supply-demand curves
- ❖ Driver incentives using repeated game strategies
- ❖ Rider-driver matching through bipartite graph matching

5.3 Alibaba and Fraud Detection

Alibaba uses statistical models and deep learning to monitor fraudulent activity:

- ❖ Graph-based fraud detection
- ❖ Time series anomaly detection

6. Mathematical Challenges and Opportunities

6.1 Scalability of Algorithms

Algorithms must scale to billions of users, products, and transactions. Efficient approximate algorithms and distributed optimization methods are in focus.

6.2 Data Quality and Noise

Poor data quality leads to poor models. Robust statistics and filtering techniques are required.

6.3 Fairness and Bias in Models

Mathematical models must account for ethical concerns. Tools from decision theory and fairness-aware learning are being developed.

6.4 Multi-Agent Systems and Strategy

With platforms involving multiple stakeholders, modeling interactions using cooperative game theory and mechanism design is gaining traction.

7. Future Directions

- ❖ **Neurosymbolic AI:** Integrating symbolic math with neural learning for robust commercial AI.
- ❖ **Federated Learning:** Privacy-aware collaborative learning models.
- ❖ **AI-driven Policy Optimization:** Governments and large organizations using math-optimized economic interventions.
- ❖ **Circular Economy Modeling:** Math for sustainability in commerce.

8. Conclusion

Mathematics lies at the heart of computational commerce. From pricing and logistics to fraud detection and recommender systems, mathematical models offer rigor, scalability, and innovation. As technologies evolve, so too will the mathematical techniques that support them. Researchers, practitioners, and policy-makers must continue to collaborate across disciplines to ensure commerce remains efficient, fair, and adaptive.

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TRANSFORMING COMMERCE AND MANAGEMENT WITH EMERGING APPLICATIONS: A CONVERGENCE OF MATH AND COMMERCE"

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Abstract

The global landscape of commerce and management is undergoing a transformative shift driven by technological innovation, data-centric strategies, and interdisciplinary integration. Among the most significant influences is the convergence of mathematical principles with commerce, particularly in areas such as predictive analytics, operations research, financial modeling, machine learning, and optimization techniques. This paper explores how mathematical methodologies are revolutionizing commercial and managerial practices, enhancing decision-making, improving operational efficiencies, and fostering innovation. It also examines emerging applications like AI, big data, blockchain, and mathematical finance, with an emphasis on how they are reshaping the future of commerce and business management.

Keywords

Mathematical modeling, commerce, management, optimization, predictive analytics, operations research, AI in business, business intelligence, financial mathematics, big data, blockchain, decision theory.

1. Introduction

The intersection of mathematics with commerce and management has become a critical domain for modern business strategies. Traditional approaches to business decision-making are no longer sufficient in the era of big data, globalization, and rapid technological changes. Mathematical tools provide robust frameworks for understanding complex systems, forecasting trends, and optimizing resources. This research investigates the multidimensional role of mathematics in transforming the commercial and management sectors. It focuses on the practical integration of mathematical theories, algorithms, and computational models to enhance business outcomes.

Objective of the Study

The primary objective of this study is to investigate the integration of mathematical principles into modern commerce and management practices. It aims to explore how mathematical tools, including modeling, optimization, and predictive analytics, are driving efficiency, accuracy, and innovation in business operations. The study also seeks to analyze current trends such as the implementation of AI, big data, and blockchain technologies through a mathematical lens, and to highlight how they are transforming strategic decision-making and commercial outcomes.

Research Problem

Despite the widespread acknowledgment of mathematics as a powerful decision-support tool, there remains a gap in understanding how mathematical frameworks are systematically applied within commercial and managerial contexts. Businesses often struggle with model implementation, interpretation, and adaptation to real-world complexity. The problem this research addresses is: How can mathematical models be effectively leveraged to enhance strategic, financial, and operational decision-making in commerce and management, especially in light of emerging technologies?

Scope of the Study

This study covers the application of mathematical methods across a range of business disciplines including finance, marketing, operations, and strategic management. It encompasses both traditional mathematical approaches like linear programming and calculus, as well as contemporary techniques powered by artificial intelligence and data analytics. The geographical scope is global, with examples drawn from multinational corporations, while the industry scope includes retail, finance, logistics, and digital services. The study is limited to mathematical applications in business and does not cover purely theoretical mathematical research or non-commercial mathematical uses.

Review of Literature

The integration of mathematics in business operations has been documented in numerous scholarly and industry publications. Anderson et al. (2021) emphasized the role of quantitative methods in managerial decision-making, while Winston (2022) provided extensive applications of operations research in logistics and planning. Ross (2014) and Hull (2021) laid the foundation for stochastic modeling and financial derivatives respectively, establishing key mathematical tools for financial risk analysis. McKinsey & Company (2018) and Davenport & Harris (2007) highlighted the growing influence of analytics and AI in redefining business intelligence. Moreover, Provost & Fawcett (2013) and Montgomery & Runger (2018) discussed data-centric thinking in managerial contexts, reinforcing the criticality of mathematical models in contemporary commerce.

Despite these contributions, the literature indicates a need for a more holistic synthesis of how these diverse mathematical tools collectively drive transformation in commerce. This study contributes to bridging this gap by presenting an integrated framework of mathematical applications across the entire spectrum of management and commercial decision-making.

Research Methodology

This study adopts a qualitative and analytical research approach supported by secondary data. The methodology involves:

- ❖ Descriptive analysis of mathematical concepts and their commercial applications.
- ❖ Case study examination to illustrate the implementation of mathematical models in leading organizations.
- ❖ Comparative review of academic and industry sources to identify patterns, benefits, and challenges of mathematical integration.
- ❖ Exploratory insights into future technological trends where mathematics will play a transformative role.

Data for the study is drawn from academic books, peer-reviewed journals, white papers, and reputable industry reports published by McKinsey, IBM, and Harvard Business Review. The research triangulates theoretical insights with practical implementations to build a comprehensive understanding of the topic.

2. Mathematical Foundations in Commerce

2.1 Algebra and Financial Transactions

Basic algebraic concepts are used in accounting, inventory management, and financial calculations. Compound interest, annuity valuations, and linear equations play a crucial role in day-to-day commercial operations.

2.2 Calculus in Economics

Calculus allows for the optimization of revenue and cost functions. Businesses use derivatives to analyze marginal cost and revenue, helping determine pricing strategies and output levels.

2.3 Probability and Statistics

In business analytics, statistics support data-driven decisions. Probability models are essential in risk assessment, insurance, investment analysis, and forecasting consumer behavior.

2.4 Linear Programming and Optimization

Linear programming is used to solve resource allocation problems. This mathematical method ensures optimal use of limited resources in logistics, production, and scheduling.

3. Applications of Mathematical Models in Commerce

3.1 Financial Modeling

Mathematical models are indispensable for valuation, forecasting, and portfolio optimization. Techniques like Monte Carlo simulation and Black-Scholes models help analyze stock options and manage risk.

3.2 Predictive Analytics in Marketing

Mathematical algorithms identify patterns in customer data, enabling targeted marketing, churn prediction, and personalized recommendations.

3.3 Inventory and Supply Chain Optimization

Inventory models like EOQ (Economic Order Quantity) and JIT (Just in Time) depend on mathematical equations to minimize holding and shortage costs.

3.4 Game Theory in Competitive Strategy

Game theory models competitive behavior and helps businesses anticipate rivals' moves, influencing pricing, marketing, and negotiation strategies.

4. Technological Integration: Emerging Mathematical Applications

4.1 Artificial Intelligence and Machine Learning

AI, driven by mathematical algorithms, enables pattern recognition, automation, and cognitive computing. In commerce, AI is used for fraud detection, chatbot services, and financial predictions.

4.2 Big Data and Business Intelligence

Big data tools utilize statistical and mathematical methods to uncover actionable insights. Businesses harness these tools for customer segmentation, market trend analysis, and strategic planning.

4.3 Blockchain and Cryptographic Models

Blockchain uses cryptography grounded in number theory and discrete mathematics for secure transactions and data integrity. It enhances transparency and trust in financial operations.

4.4 Internet of Things (IoT) and Real-Time Decision-Making

IoT generates real-time data which is processed using mathematical models to optimize logistics, maintenance, and inventory.

5. Operations Research in Management

Operations research (OR) applies mathematical models to solve complex managerial problems. Key OR applications include:

- ❖ Transportation and Logistics Planning
- ❖ Workforce Scheduling
- ❖ Project Management using CPM/PERT
- ❖ Network Models for Supply Chain Design
- ❖ Simulation Modeling for Risk Analysis

6. Financial Mathematics and Risk Management

6.1 Quantitative Finance

Quantitative finance relies on differential equations, stochastic processes, and statistical models. Applications include pricing derivatives, managing financial portfolios, and optimizing asset allocation.

6.2 Actuarial Science

Actuarial models use probability theory to assess risks in insurance and pension planning.

6.3 Credit Scoring and Fraud Detection

Mathematical algorithms evaluate creditworthiness and flag suspicious transactions using anomaly detection techniques.

7. Mathematical Decision-Making Tools

7.1 Decision Theory and Bayesian Analysis

Bayesian networks and decision trees assist in making optimal decisions under uncertainty.

7.2 Multi-Criteria Decision-Making (MCDM)

MCDM methods such as AHP (Analytic Hierarchy Process) and TOPSIS (Technique for Order of Preference by Similarity to Ideal Solution) support complex managerial decisions involving multiple criteria.

7.3 Simulation and Scenario Analysis

Simulation models, including Monte Carlo simulations, evaluate outcomes of various business scenarios, helping plan under uncertainty.

8. Case Studies: Real-World Implementations

8.1 Amazon's Predictive Logistics

Amazon uses statistical modeling to predict customer orders, enabling anticipatory shipping and efficient inventory management.

8.2 Walmart's Data-Driven Supply Chain

Walmart integrates mathematical forecasting and optimization models to reduce costs and improve product availability.

8.3 Financial Institutions using Risk Models

Banks apply advanced mathematical models for stress testing, credit risk analysis, and compliance with regulatory standards.

9. Challenges and Limitations

Despite the advantages, integrating mathematics in commerce faces hurdles:

- ❖ Data Quality and Availability
- ❖ Skill Gaps in Mathematical Expertise
- ❖ Interpretability of Complex Models
- ❖ Cost and Implementation Barriers

Overcoming these requires education, technological investments, and interdisciplinary collaboration.

10. Future Trends

10.1 Quantum Computing

Quantum algorithms could revolutionize optimization, cryptography, and data analysis in commerce.

10.2 Explainable AI (XAI)

With increasing demand for transparency, mathematical efforts are shifting toward interpretable AI models.

10.3 Integration of Environmental and Ethical Metrics

Mathematical models are being adapted to include sustainability, ESG (Environmental, Social, and Governance) indicators, and ethical considerations.

11. Conclusion

Mathematics is more than a foundational discipline—it is a transformative force in commerce and management. Through the integration of mathematical reasoning, data science, and emerging technologies, businesses can harness deeper insights, make informed decisions, and stay competitive in a complex global market. The convergence of math and commerce heralds a new age of intelligent enterprise, where optimization, prediction, and precision define the core of management practices. For academia, industry, and policymakers alike, the synergy between mathematics and commerce offers a roadmap to future-proof operations and foster innovation in a data-driven economy.

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AN ANALYSIS OF ASSET QUALITY IN INDIAN PUBLIC SECTOR BANKS: A TURNAROUND STORY FRAUGHT WITH NEW CHALLENGES

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Abstract

This working paper examines the significant transformation in the asset quality of Indian Public Sector Banks (PSBs) over the last decade. Plagued by the "twin balance sheet" problem, PSBs saw their Gross Non-Performing Assets (GNPAs) peak at alarming levels in 2018. This paper analyzes the trajectory of asset quality, identifying the key drivers behind the subsequent cleanup and recovery. We find that a combination of transparent recognition under the Asset Quality Review (AQR), the resolution mechanism provided by the Insolvency and Bankruptcy Code (IBC), aggressive provisioning, substantial government-led recapitalization, and improved credit discipline have been instrumental in this turnaround.

Using data from Reserve Bank of India (RBI) reports, we demonstrate a sharp decline in GNPA and Net NPA ratios, coupled with a robust increase in the Provisioning Coverage Ratio (PCR) and Capital to Risk-weighted Assets Ratio (CRAR). However, the paper also highlights emerging challenges, including potential stress in the MSME and unsecured retail loan portfolios, risks from restructured assets post-COVID-19, and the persistent need for governance reforms. We conclude that while PSBs have achieved a remarkable balance sheet repair, sustained vigilance, enhanced risk management frameworks, and continued structural reforms are imperative for ensuring long-term financial stability.

JEL Codes: G21, G28, G32, E58