

A Study on Applications of Operations Research Techniques

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Abstract:

Operations Research plays a vital role in solving complex decision-making problems encountered in engineering, management, and service systems. This paper presents an overview of the application of major Operations Research techniques such as queuing theory, graph theory, replacement theory, inventory management, job scheduling and job sequencing. These techniques provide systematic and quantitative approaches to optimize resource utilization reduce operational costs and improve system efficiency. Through the study of various applications, the paper highlights how mathematical modelling and analytical methods support effective planning and decision-making in real-world situations.

Keywords: Operations Research, Queuing Theory, Graph Theory, Replacement Theory, Inventory Management, Job Scheduling, Job Sequencing

Introduction

Modern decision-making problems in engineering, management, biology, education and service systems are characterized by complex interactions, limited resources, uncertainty, and dynamic behaviour. Classical deterministic approaches often fail to capture these complexities, leading to inefficient planning and suboptimal performance. As a result, applied mathematical theories such as queuing theory, replacement and renewal theory, scheduling theory, graph theory and mathematical modelling have emerged as powerful tools for analyzing and optimizing real-world systems.

The reviewed literature demonstrates that these theories are not merely abstract mathematical constructs but have wide-ranging practical applications. Queuing theory has been successfully applied to banks, healthcare systems and traffic flow and service delivery to minimize waiting time and improve resource utilization. Scheduling and sequencing models address production planning, single-machine shops and service operations by optimizing job order, due date assignment, and common resource usage. Replacement and renewal theories support maintenance planning, pavement design, warranty analysis, and equipment management by determining optimal replacement policies that minimize long-term cost.

Graph theory has proven effective in modelling complex networks across diverse domains such as transportation systems, biological networks, protein flexibility analysis, landscape connectivity, and computer science. By representing system components as nodes and interactions as edges, graph-based models provide insights into connectivity, robustness and critical elements within a system. Similarly, mathematical modelling and computer simulation play a crucial role in understanding complex biological processes such as blood coagulation and in enhancing mathematics education through real-world problem modelling.

Inventory management studies further emphasize the importance of quantitative methods in small and medium enterprises, highlighting how structured decision models improve operational efficiency and financial performance. Across all these domains, the common objective is system optimization under constraints, achieved through mathematically grounded, application-oriented approaches.

This research paper builds upon the above studies to present a unified perspective on the application of applied mathematical theories in solving practical problems. By reviewing and integrating these applications, the paper aims to highlight their relevance, effectiveness, and potential for further interdisciplinary research.

2. Definitions

2.1 Queuing Theory

Queuing theory is the mathematical study of waiting lines, where customers arrive to receive service from one or more servers. It is used to analyze system performance measures such as waiting time, queue length, and server utilization, with applications in banking, healthcare, traffic systems, and service delivery.

2.2 Scheduling and Sequencing

Scheduling refers to the allocation of resources over time to perform a collection of tasks, while job sequencing determines the order in which jobs are processed. These concepts are applied in manufacturing and service systems to minimize completion time, tardiness, and resource conflicts, especially in single-machine and resource-constrained environments.

2.3 Replacement Theory

Replacement theory deals with determining optimal policies for replacing items that deteriorate, fail, or become obsolete over time. The objective is to minimize total cost by balancing maintenance, replacement, and operational expenses. Applications include equipment maintenance, pavement design life analysis, and infrastructure management.

2.4 Renewal Theory

Renewal theory is a probabilistic framework that analyzes the timing of repeated events such as system failures and replacements. It is widely applied in warranty analysis, maintenance planning, and reliability engineering to model system life cycles and expected costs.

2.5 Inventory Management

Inventory management involves planning and controlling the ordering, storage, and usage of goods to meet demand efficiently. Mathematical inventory models help organizations minimize holding, ordering, and shortage costs, particularly in small and medium enterprises.

2.6 Graph Theory

Graph theory is a branch of mathematics that studies networks composed of nodes and edges. It is applied to analyze connectivity, flow, and structure in systems such as transportation

networks, biological networks, protein structures, landscape ecology, and computer algorithms.

2.7 Mathematical Modelling

Mathematical modelling is the process of representing real-world systems using mathematical expressions to analyze behaviour, test hypotheses, and predict outcomes. It is extensively used in biological systems, education, and engineering to understand complex processes that are difficult to study experimentally.

2.8 Computer Simulation

Computer simulation involves using computational models to imitate the behavior of real systems over time. It complements mathematical modeling by allowing experimentation under varying conditions and constraints, particularly in complex and nonlinear systems.

The reviewed definitions and applications demonstrate that applied mathematical theories provide systematic reliable, and efficient solutions to complex real-world problems. By integrating these approaches, the present research contributes to the growing body of interdisciplinary work that bridges theory and practice.

Queuing theory is applied to analyze and optimize waiting-line systems by minimizing customer waiting time and improving service efficiency. It is widely used in banks, hospitals, traffic systems and service organizations for effective resource allocation and congestion control. Vandaele et al [26] in 2000 demonstrated that G/G/1 model and the state-dependent G/G/1 model could be applied to analyze traffic flow on a real highway segment in Belgium (E19 St.-Job → Merksem). The study aimed to use analytical queuing models to construct speed–flow–density diagrams, which traditionally were built empirically, to incorporate variance in arrivals and departures, to analyze realistic highway congestion patterns and to evaluate the impact of variability on traffic speed and performed what-if and sensitivity analyses.

The study used hourly traffic counts for a real Belgian highway (E19), recorded across 1993–1995 showing that traffic peaked at 8:00 AM (~3200 veh/hr), a long plateau of ~2000 vehicles/hr from 9 AM to 7 PM and maximum observed flow was 4350 vehicles/hr. First study used the G/G/1 queues producing analytical speed–flow, flow–density, and speed–density diagrams under different variance assumptions. It was shown that higher variance implied lower speeds and variance in arrivals (ca) had a larger impact than variance in service (cs). After that study used a state-dependent model where the nominal speed SN depended on traffic flow and speed–density and speed–flow diagrams were also constructed. In this case it was found that the exponential model predicted a sharp drop in speed as flow increase, at moderate flows, speeds might collapsed to 20 km/h and linear model predicted smoother decline. Strengths of the study were using real world data made the study empirically meaningful, applying multiple queuing models, constructing analytical speed–flow–density diagrams and capturing effects of variability and supporting environmental analysis. Assuming single-lane, single-server flow, not capturing shockwaves, merging, headway

behaviour, producing infeasible speeds frequently and not providing stochastic simulation for comparison were some weaknesses of the study. Overall, the study was methodologically rigorous, deeply mathematical, and introduced one of the more sophisticated uses of queuing theory for uninterrupted traffic flow.

Obamiro[19] in 2010 applied queuing theory in the ante-natal care unit of a public teaching hospital in Lagos, Nigeria, using M/M/C queuing system, to provide a systematic, quantitative framework for analyzing patient flow, evaluating operational efficiency and improving overall service delivery. Since antenatal clinics often experience unpredictable and uneven patient arrivals so mathematical modelling became essential to identify congestion points, estimate waiting times and determine optimal resource allocation. Queuing theory was implemented by collecting real-time data on patient arrivals, service durations and the number of available medical personnel. Through structured observations conducted over three consecutive weeks Monday, Tuesday and Wednesday, which were the busiest clinic days the study quantified the arrival rates (λ), service rates (μ), and number of active servers (C). These inputs were analyzed using the TORA optimization system. By quantifying waiting times the model identified periods of service congestion which allowed healthcare managers to make informed, data-driven decisions to minimize delays, the model demonstrated that even small changes in staffing patterns could dramatically alter waiting times for example increasing the number of doctors could substantially reduce W_q and L_q as proper scheduling of personnel according to peak arrival periods prevent system congestion. Identifying low- and high-demand intervals supports more dynamic and flexible deployment of staff. The study provided a diagnostic tool for continuous performance monitoring within the ante-natal care workflow. The study also provided flexibility of the M/M/C model by combining software tools like TORA which made it adaptable to diverse clinical scenarios, supporting optimization across the entire hospital system. Hence by demonstrating how quantitative models could enhance daily operations, the study encouraged broader adoption of queuing-based decision-making within healthcare management. The effective application of study allowed health administrators and policymakers to understand system bottlenecks and delays, evaluated the efficiency of current staffing levels, optimize scheduling to reduce patient waiting time, improved service quality and patient satisfaction and made informed decisions about expansion or modification of services. Punnakitikashem et al [22] in 2012 used SERVQUAL model to evaluate the effectiveness of a service quality in hospital after implementing Lean management. The study focused on measuring patient expectations and perceptions across five key service dimensions reliability, responsiveness, assurance, empathy and tangibility using data from 450 patients. The study aimed to understand whether Lean implementation improved overall service quality. The study used a 24-item SERVQUAL questionnaire, five service dimensions, a perception vs. expectation rating method and a 5-point Likert scale to collect data. The study conclude that service quality was moderate, lean had positively impacted tangibility through cleaner, more organized spaces, assurance dimension performed poorly so patients lack trust/confidence in staff and no significant difference between overall expectation and perception. It was highlighted that tangibility improvements was a clear win for Lean, assurance was a crucial gap needing

management attention and reliability, responsiveness and empathy needing moderate improvement. Strengths of the study were using strong methodological structure, use of valid SERVQUAL instrument, using high-quality sample size (450 respondents), excellent reliability (Cronbach's $\alpha > 0.7$), clear dimension-wise analysis and showing positive influence on tangibility by Lean. Weaknesses were SERVQUAL did not measure actual Lean performance outcomes, assurance gap lacked operational explanation and evaluated only outpatient setting. Overall, the study provided a meaningful assessment of service quality, though deeper integration with Lean performance data would strengthen its conclusions. Anokye et al [3] in 2013 focused on analyzing vehicular traffic flow at the Oforikrom signalized intersection using an M/M/1 queueing model with the goal to determine whether the current traffic-light settings efficiently managed arrival and departure of vehicles and to suggest strategies for reducing congestion. The study used data recorded during morning, afternoon, and evening peak sessions from three major routes entering the intersection which included average number of arriving cars per session, average service rate (cars leaving the intersection) and time durations for arrival and service intervals. $\rho < 1$ in all sessions showed that service capacity exceeded vehicle arrival rates and the system was stable and congestion increased in the evening, not because of arrival-service imbalance, but due to driver behaviour, especially illegal stopping near signals when MTTU officers were absent. The study recommend that enforcing traffic regulations, especially in the evening, preventing commercial drivers from stopping near the signal, encouraging use of bicycles to reduce congestion and improving public transport to reduce private car reliance. The strengths of the study included use of real-world traffic data, correct computation of queueing parameters, and logical interpretation of findings, combines engineering modelling with behavioural observations and producing practical recommendations for policymakers. M/M/1 did not reflect multiple lanes or turning flows, no simulation of optimized traffic signal times was done, use of limited statistical analysis of arrival patterns and not accounting for pedestrian factors or mixed traffic (cars, bikes, buses) were some weaknesses of the study. The study successfully showed that queueing metrics could diagnose operational inefficiencies and revealed that human behaviour may be a stronger cause of congestion than signal timing. Marsudi and Shafeek[18] in 2014 improved the performance of a multi-stage production line of injection molding, first color spray, second color spray, UV spray, assembly and packing workstation. The study was practical, data-driven, and directly tied to real manufacturing operations. The goal was to use queueing theory to model a multi-stage production line, analyze performance indicators such as utilization, queue length, idle time, waiting time, to identify bottlenecks in the manufacturing workflow and to suggest improvements to increase efficiency. The study revealed important performance insights as packing had very high queue time (76% queue rate) which was much higher than other workstations (20–42%) and caused by mismatch between assembly output and packing speed. Efficiencies across workstations varied widely assembly rate was 80.98% (very efficient), UV at 67.97%, 1st/2nd colour spray were moderate and packing was at 37.38% (very low). It was recommended to increase packing operators from 5 to 10 could raise efficiency from 37.38% to 99.94%. Strengths were using real data from a multinational battery company, making the

findings practically useful, providing multi-stage analysis, finding quantitative performance metrics, providing actionable recommendations and using high model accuracy. Some weaknesses were assumption of independent queues, lacking multi-server modelling and batch process handling was oversimplified. The study successfully identified performance problems in a complex multi-stage production line and provided actionable decision support for improving efficiency. In 2015 Paul [21] presented the use of queuing theory as a diagnostic and improvement tool for service delivery in Federal Polytechnic, Nasarawa, with particular emphasis on the student registration process. The study sought to identify the queuing structure, queuing discipline and service mechanism used during student registration, to examine how long queues affected service delivery, to show how queuing models could guide improvements in registration efficiency and to provide practical recommendations to reduce waiting time. The study identified and described the components of the registration process as a queuing system and a hypothetical single-channel queuing model with arrival rate 40 students per hour and service rate as 48 students per hour was applied. The study was effective as a descriptive and awareness building exercise, showing that queuing theory was relevant to service delivery problems in educational institutions. However, it was less effective as a rigorous quantitative application, since it did not estimate arrival/service rates from real data did not test alternative queuing configurations and did not simulate improvements quantitatively. Some strengths were addressing common operational problem in Nigerian higher institutions, translating registration activities into arrivals, servers, queues and discipline was well articulated, leading to practical recommendations of full online registration, to increase number of servers and decentralization of registration points. Limitations were using assumed data, use of oversimplified queuing and not making comparison between calculated waiting times and actual observed waiting times. The application was best viewed as an introductory applied study, suitable for policy discussion and managerial awareness, rather than a fully developed operational queuing analysis. In 2016 Koka and Badshah[15] analysed service efficiency in a branch of Canara Bank, Indore, using the M/M/C queuing model supported by Birth–Death Markov processes. The study attempted to demonstrate that queuing theory could be used to diagnose performance issues in service systems, particularly in banking environments where customer arrivals were stochastic and service times vary. Data related to number of arrivals, service completions, actual service times and waiting times was collected for 15 days between 10:30 AM and 4:30 PM. The arrival rate was computed as 0.44 per minute, service rate was 0.68 per minute with 4 servers. The system utilization factor was 0.1594 significantly below 1, leading to conclude that the bank had more than adequate service capacity. Customers rarely waited, as servers were almost always available and the multi-server structure eliminated congestion in the banking hall. The study yielded practical recommendations of multi-server banking systems for reducing congestion and stress for customers. The study addressed only one scenario (with 4 tellers) by adding additional scenarios such as service capacity during peak customer times or reducing the number of servers would have provided a more robust assessment. The paper dedicated heavy space to advanced Markov and birth–death theory but only a small portion to real application. The study reinforced the importance of multi-server configurations to

eliminate excessive waiting and promote service efficiency. The study offered clear insights into the impact of adequate service capacity on customer waiting time and operational performance, confirming that multi-server systems enhanced customer satisfaction and reduce congestion.

Graph theory is applied to model and analyze complex networks by representing system components as nodes and their interactions as edges. It is widely used in transportation planning, communication networks, biological systems and social network analysis to study connectivity and optimize performance. Bunn et al [7] in 2000 applied graph theory as a practical conservation tool to evaluate landscape connectivity in fragmented ecosystems. The landscape was modelled as a network in which habitat patches were treated as nodes and movement pathways between patches were treated as edges, allowing ecological connectivity to be analyzed using established graph operations. The study was applied in contribution to the focal-species framework, where graph models were constructed separately for species with different dispersal abilities. By applying the model to American mink and prothonotary warblers, the study demonstrated that the same landscape could function as connected or fragmented depending on species-specific movement capacity. The study applied least-cost path analysis to define functional distances between habitat patches, improving ecological realism over simple Euclidean measures. Graph operations such as edge thresholding, node removal and minimum spanning trees were applied to simulate habitat loss, identify critical patches and assess landscape resilience. These applications provided actionable insights for prioritizing habitat protection and restoration. The study effectively demonstrated that graph theory could support practical conservation decision-making, particularly in assessing connectivity, fragmentation and metapopulation viability at landscape scales. Jacobs et al.[14] in 2001 presented an application of graph theory to structural biology, specifically for predicting protein flexibility and rigidity from a single static three-dimensional structure. The study applied graph-theoretical rigidity analysis to model proteins as bond-constraint networks, where atoms were treated as vertices and covalent bonds, hydrogen bonds and salt bridges were represented as edges imposing distance and angle constraints. The study demonstrated the application of this approach through case studies of biologically significant proteins HIV protease, dihydrofolate reductase and adenylate kinase. In each case, the predicted flexible regions corresponded closely with experimentally observed conformational changes involved in ligand binding and enzymatic activity. Another important application was the use of hydrogen-bond energy thresholds to tune the rigidity of the protein network by selectively including or excluding weaker hydrogen bonds, the method simulated the environmental or binding conditions that affected protein stability. The flexibility index introduced in the paper further extended the application by offering a quantitative, continuous measure of local flexibility, enabling comparative analysis across different regions of a protein which allowed researchers to pinpoint mechanically critical residues and domains. The application effectively showed that graph theory could serve as a powerful computational tool in protein science, supporting rapid flexibility prediction, functional interpretation of protein motion and aiding drug design by identifying structurally sensitive regions. Goldberg and Harrelson[9] in 2003 addressed one of the most practically significant problems in

computer science and operations research that was efficient point-to-point shortest path computation in very large directed graphs, particularly road networks by translating advanced graph-theoretic ideas into a scalable solution suitable for real-world navigation systems. The study was motivated by real-world systems such as digital map services (e.g., driving directions), GPS navigation devices and large-scale transportation networks. The problem was Point-to-Point (P2P) shortest path problem where input was a large directed graph with nonnegative edge weights to compute the exact shortest path between two arbitrary vertices where preprocessing was allowed, but extra storage must remain linear in graph size. The study applied A* search enhanced with graph-theoretic lower bounds derived from landmarks and the triangle inequality. This approach was known as the ALT method (A* + Landmarks + Triangle inequality). In method was applied to a small number of strategically chosen landmarks, distances were to and from these landmarks which were precomputed and during query time, these distances provided a strong lower bounds that guided the A* search. The strongest application in the study was the large-scale experimental evaluation on real road networks derived from Microsoft MapPoint data. The algorithms were tested under realistic assumptions, including memory limitations and repeated queries, making the study highly credible and industry-relevant. The authors applied bidirectional A* variants to further enhance performance, to reduce search space from both the source and destination simultaneously. The study was validated through extensive benchmarking on real and synthetic graphs, comparison against Dijkstra, bidirectional Dijkstra and Euclidean A* and output-sensitive performance measures (vertices scanned vs. path length). It was shown that ALT-based applications scanned as few as 4–30 vertices per path vertex, even in graphs with millions of nodes, demonstrating exceptional scalability. Strengths of the study were highly scalable real-world applicable, helped in finding exact shortest paths (not approximate) and were effective on road networks where geometric heuristics failed. Limitations of study were requiring careful landmark selection, domain dependent performance gains and less effective where graph structure lacked spatial coherence. By combining A* search with landmark-based graph-theoretic bounds, the study delivered a solution that was practically deployable, theoretically sound and empirically validated at scale. Thomson and Richardson [25] focused on using graph-theoretic techniques to automatically structure, classify and generalize road network data for cartographic and GIS use. The system was implemented in POP-II and provided results using a real network from a Vancouver Island map sheet. This study represented a shift away from traditional manual or rule-based generalization toward a data-driven, context-sensitive, automated approach. This study aimed to create a system that automatically structured raw road data, classified road segments based on functional relevance, generated hierarchical representations and supported density reduction while preserving connectivity. The core of the study was the use of shortest path spanning trees (SPSTs) and Shreve magnitudes to determine the functional relevance of each road segment. The study blended geometric data (road length, shape), thematic data (number of lanes, surface type) and topological data (nodes, arcs, intersections). It was shown that major routes naturally received higher importance scores, less important local roads received minimal weighting, travel-time cost produced more realistic hierarchies than length alone and

enhancing the major SPST ensured connectivity during generalization. Strengths of the study were demonstrating the emergence of classification automatically, producing consistent and logical road hierarchies, handling complex networks with cycles and multiple paths and eliminating the need for manual coding or subjective choices. Some limitations were high computation times for large datasets, overweight nodes with arbitrarily high assigned importance and current implementation handled only one hierarchy level at a time. The study could be directly used for map generalization at smaller scales, navigation hierarchies for routing, GIS data classification, database creation when starting from raw unstructured data and multi-scale mapping. The study was innovative, practical and theoretically strong, it successfully demonstrated the application of graph theory especially SPSTs and Shreve magnitudes to automate road network generalization. In 2007 Stam and Reijneveld[24] discussed a major interdisciplinary advance, where graph theory was systematically applied to understand the structure and function of brain networks. The aim of the study was to determine whether brain networks exhibited small-world, random, or scale-free properties and way these properties were related to normal cognition and neurological disorders. The study was applied to neuroanatomical data from organisms such as cats, macaques and humans and applied graph theory to represent brain regions as nodes and anatomical connections as edges, to compute clustering coefficients and path lengths and to demonstrate that anatomical brain networks exhibited small-world topology. One of the most important applications in the study was the extension of graph analysis to functional connectivity data. Using graph theory time series were obtained from fMRI, EEG, or MEG recordings and statistical interdependence (correlation, synchronization likelihood) was computed. Correlation matrices were converted into graphs and network measured efficiency and betweenness. Strengths of the study were using unified analytical framework, connecting structure, function and dynamics, demonstrating strong biological interpretability and offering clinical relevance for brain disorders. Some limitations were sensitive to noise and recording artefact, limited spatial resolution in EEG/MEG-based applications and depending on thresholding in functional connectivity graphs. The application of graph theory in this paper was comprehensive, innovative and highly impactful. It convincingly demonstrated that the brain could be understood as a complex network optimized for efficiency and adaptability. Gao et al [8] in 2017 applied graph theory for understanding complex biological systems. Biological entities such as genes, proteins, metabolites and neurons were modelled as nodes, while their interactions were represented as edges. This application enabled the transformation of large-scale biological data into structured networks that could be quantitatively analyzed. A key application of the paper was in gene regulatory networks, where graph-based representations helped to identify regulatory relationships among genes. The study also applied graph theory to protein–protein interaction (PPI) networks, allowing the identification of hub proteins that played critical roles in cellular stability and function. This application was supported by biological interpretation by linking network topology to protein essentiality and disease association. The important application of the study was in metabolic networks, where metabolic reactions were represented as directed graphs which helped to analyze metabolic pathways, to detect bottlenecks and to understand system-level

metabolic regulation, which was valuable in biotechnology and drug development. The study applied graph theory to study brain connectivity and signal transmission. Measures such as clustering coefficient and path length were used to interpret information flow and functional organization in neural systems. The study demonstrated that graph-theoretic applications enabled system-level biological insights that were difficult to obtain through traditional reductionist methods. By focusing on connectivity, structure, and interaction patterns, the application of graph theory supported biological discovery, disease analysis and therapeutic targeting.

Replacement theory is applied to determine the optimal time for replacing deteriorating or obsolete items in order to minimize total operating and maintenance costs. It is widely used in equipment maintenance, infrastructure management and reliability planning. Robinson and Devarakonda [23] in 1990 addressed a practical and performance-critical problem in computer systems for efficient data cache management for file systems, database management systems and disk controllers. The authors applied a novel frequency-based replacement (FBR) strategy to improve cache performance beyond what was achievable with the commonly used Least Recently Used (LRU) policy. The core application lied in combining reference frequency with recency information cache blocks were divided into new, middle and old sections, reference counts were incremented only after blocks leave the new section, effectively factoring out locality and replacement candidates were chosen exclusively from the old section. The algorithm was applied using trace-driven simulations on five real-world workloads, including UNIX file systems, VM systems and large commercial MVS systems. These traces represented diverse computing environments such as research computing, software development and transaction processing. The study carefully modelled realistic cache operations, including reads and writes, delayed write-back and block replacement and eviction. The performance was measured across cache sizes ranging from 800 KB to 32 MB, allowing the authors to study behaviour near the knee of the miss-ratio curve, where cache optimization was most valuable. The simulation results demonstrated that FBR consistently outperforms LRU in most workloads, performance improvement reached up to 34% relative to the gap between LRU and OPT and the greatest benefit occurred at intermediate cache sizes. Using real system traces, increasing credibility, applicable to multiple system types (UNIX, VM, MVS, maintaining low implementation overhead comparable to LRU and demonstrates clear quantitative performance gains were some strengths of the study. Requiring tuning of multiple parameters and relying on trace-driven simulation rather than live deployment were some limitations. The study of frequency-based replacement in this paper is practical, well-validated and highly relevant to data cache management. Le and Gascuel [17] in 2008 focused their study on demonstrating the hinge-loss Markov random field (HL-MRF) based optimization framework and machine-learning driven estimation that could be used to construct improved amino acid replacement matrices that outperformed classical matrices (like PAM, BLOSUM) when applied to biological sequence analyses. The study used large, diverse aligned protein sequences to estimate substitution behaviour. The model aggregated information across thousands of data points the HL-MRF model computed optimal replacement scores using convex optimization, which guarantees

convergence and computational efficiency. The system applied smoothing and regularization to avoid overfitting and to produce interpretable replacement probabilities. The final output was a complete 20×20 substitution matrix with replacement likelihoods and it was found that the new matrix aligned well with respected evolutionary trends, frequently similar amino acids (e.g., those sharing physicochemical properties) showed strong mutual replacement scores. The topology of the replacement space matched known biological expectations. Strengths of the study were demonstrating a modern machine-learning framework for bioinformatics, producing interpretable amino acid relationships, providing clear comparisons against established matrices, showing computational advantages (convexity, scalability) and linking statistical output to biological intuition (clusters, conservation). Some weaknesses were not describing data origin, not doing phylogenetic tree reconstruction tests and doing limited discussion of computational time or complexity. The study demonstrated clear advantages over classical approaches and by applying HL-MRFs and convex optimization to real protein data, the study showed that their method could generate a scientifically valid, data-driven amino acid replacement matrix. Bagui et al [4] in 2012 presented applications of replacement theory to civil engineering specifically to determining the economic life of pavement and bridges. The paper aimed to use replacement theory to determine optimal replacement year, to support cost-effective pavement and bridge renewal decisions, to avoid unnecessary rehabilitation or delayed reconstruction and to develop a structured OR-based method for infrastructure replacement. The study used two versions of replacement theory replacement without discounting and replacement with discounting. Collected pavement data showed that initial pavement cost was Rs 50 million per km, routine maintenance cost was Rs 0.3 million, functional overlay at years 5, 15, 25, structural overlay at years 10, 20, 30, % annual increase in maintenance costs and 12% discount rate. The study found that weighted average cost of pavement decreased until around 15 years and even after cost changed, the replacement year remained stable at 15. The study also tested replacement theory on a 45 m bridge. Collected bridge data showed that initial cost was Rs 15 million, annual maintenance was 0.5% of initial cost, annual increase was 6%, periodic maintenance every 5 years and bearing replacement was every 20 years. The discounted cost analysis showed an extremely long economic life of around 49 years, just before a large maintenance spike. Strengths of the study were using actual traffic, maintenance, and cost data, making the results credible, using practical decision rules, doing sensitivity analysis and using model in civil engineering. Weaknesses were depending heavily on accurate cost data, not incorporating traffic growth uncertainty, replacement decision assumed deterministic conditions only and case studies were limited to two projects. The application was strong, methodologically sound, and a significant contribution to infrastructure management decision-making. Blischke and Scheuer [6] presented practically important applications of renewal theory to the economic evaluation of free-replacement warranties. The study developed a renewal-based framework to determine the long-run expected profit and cost consequences when a manufacturer offered a warranty under which all failed items were replaced free of charge for a fixed period. The study aimed to apply renewal theory to evaluate the long-run expected number of warranty payments, to determine expected profit for manufacturers offering free replacement,

understand how failure distributions affected warranty cost and to derive approximations for renewal functions in cases where exact solutions did not exist. Under a free-replacement warranty the buyer paid a one-time cost and received free replacements of failed items until warranty time and after the warranty period ended, revenue was not received until the item in service failed again creating random-length cycles. The study showed that the exponential distribution gave closed-form expressions for renewal function and uniform distribution was used to illustrate mixture formulation. For gamma and Weibull distributions, the renewal function had no closed-form, so the study applied renewal approximations, numerical tables and simulation. The elementary renewal theorem overestimated warranty costs consistently but the asymptotic renewal approximation performed well (within 1–2%), showing that renewal theory could be practically used for warranty cost estimation. Helping manufacturers in setting warranty price, covering multiple lifetime distributions and validating theoretical approximations by simulation were some strengths of the study. Not using real world data, assuming instantaneous replacement, assuming identical replacement cost and lifetime and assuming constant life cycle were some limitations of the study. The study successfully demonstrated that renewal functions, excess life distributions and asymptotic approximations could be used to compute expected warranty costs, forecast long-run profit, evaluate different failure distributions and guide manufacturers in decision-making.

Job sequencing is applied to decide the most efficient order in which jobs should be processed on a machine or system. It helps minimize total processing time, waiting time, and delays in manufacturing and service operations. Veen et al [27] in 1998 applied job sequencing and scheduling theory to production and service systems in which multiple jobs compete for shared or common resources such as tools, machines, operators or auxiliary facilities. The study addressed a realistic operational challenge frequently encountered in manufacturing environments, where efficient sequencing must consider not only processing times but also resource availability and conflicts. The study was applied in manufacturing and assembly systems where jobs required a common secondary resource in addition to machine time. The study demonstrated the role job sequencing and scheduling of in minimizing idle time, delays and resource contention could be minimized. By developing rules for a single-machine and multi-job environment it was illustrated that optimal or near-optimal job orders could be determined when shared resources imposed additional constraints. Through numerical illustrations, the study showed improvements in key performance measures such as total completion time, machine utilization and waiting time. The study was applied to service operations, including repair facilities, healthcare unit and project-based work environments where specialized equipment or skilled personnel must be shared across tasks. The sequencing approach helped to ensure fair and efficient allocation of limited resources while maintaining service quality. The study demonstrated that incorporating common resource constraints into job sequencing lead to more realistic and implementable schedules, improving operational efficiency and decision-making in resource-constrained environments. Ataulakhanov and Panteleev [1] in 2005 applied mathematical modelling and computer simulation as practical tools to understand, analyze and predict the behaviour of the blood coagulation system. One major application of the study was use of mathematical

models to analyze mechanisms of coagulation reactions, particularly membrane-dependent processes such as tenase and prothrombinase activity. Models were applied to determine the order of enzyme–cofactor–substrate complex assembly and mechanism of substrate delivery (free vs. membrane-bound substrate) providing regulatory role of inhibitors and feedback loops. The study applied modelling to investigate activation thresholds, feedback regulation and cascade dynamics within the coagulation system. Through computer simulations, the study demonstrated positive and negative feedback loops to generate threshold behaviour, ensuring that coagulation was activated only under appropriate conditions. This application was crucial for understanding the way system avoided unwanted clot formation while remaining responsive to vascular injury. Mathematical models were applied to interpret laboratory coagulation tests including Thrombin generation assays, Prothrombin time (PT) tests and activated partial thromboplastin time (APTT) tests. By simulating these assays, the models helped identify key parameters affecting test sensitivity and improve the interpretation of clinical data. The study highlighted the applications of modelling in drug design and evaluation, particularly for anticoagulant therapies. Simulations were used to predict the effects of inhibitors, explore dose–response relationships, and assess system sensitivity, thereby supporting rational drug development strategies. The study established modelling as an essential applied tool for mechanistic insight, experimental guidance and clinical relevance in hemostasis and thrombosis research. Xia et al[29] in 2008 applied job sequencing and due date assignment techniques to improve scheduling decisions in a single-machine production environment by addressing a common operational problem faced by manufacturing and service organizations, where multiple jobs competed for a single processing facility and must be completed within assigned delivery dates. The study applied simultaneous determination of job sequence and due dates, rather than treating these decisions independently which reflected real-world scheduling practices, where job order and delivery commitments influenced each other. The study applied the proposed models to minimize performance measures such as total completion time, tardiness, earliness and due date-related penalties which was particularly useful for production managers seeking to balance operational efficiency with customer satisfaction. By assigning realistic due dates based on processing requirements, the model helped to avoid excessive lateness and unnecessary early completion. The study was applied in service systems, such as maintenance facilities, printing services and repair workshops, where a single resource must handle multiple customer jobs. The study was further strengthened by numerical examples that illustrated that the sequencing and due date assignment rules could be implemented step by step. These examples demonstrated the practicality of the approach and its adaptability to different operational contexts. The application presented in this study was practical and managerially relevant, demonstrating the way to coordinated job sequencing and due date assignment to improve operational efficiency and customer service in single-machine shops. In 2014 Erbaş et al.[10] applied mathematical modelling as an instructional approach in mathematics education, emphasizing its role in connecting mathematical concepts with real-life situations. This application aimed to distinct between two modes of application modelling as the aim of teaching mathematics, where students were taught existing mathematical

models and then apply them to real-life problems and modelling as a means of teaching mathematics, where modelling activities were used to help students develop mathematical concepts organically. The paper applied modelling through Model-Eliciting Activities, which were designed tasks that required students to collaboratively construct, test and refine models. This application highlighted modelling as a social and iterative classroom process, encouraging discussion, justification and revision of ideas. Another significant application was the integration of modelling into school curricula by illustrating that modelling tasks could be aligned with curricular goals and standards, supporting development of problem-solving, reasoning and interpretation skills students. This study showed that modelling was a bridge between curriculum content and real-world relevance. The application of modelling was linked directly to the development of key competencies such as problem formulation and interpretation, use of multiple representations, validation and refinement of solutions and critical and analytical thinking and through these applications, modelling became a tool for competency-based mathematics education, rather than a supplementary activity. The study showed that through classroom activities, curriculum design, and competency development, modelling had strong potential to enrich mathematics education. Zhu et al. [30] in 2016 presented an advanced application of scheduling theory to realistic manufacturing and service systems, where job processing was influenced simultaneously by learning effects, consumable resource allocation and past-sequence-dependent setup times. The application addressed limitations of classical scheduling models that typically consider machines and processing times in isolation, making the proposed framework highly relevant for real operational environments. A major practical application lied in manufacturing systems, particularly in high-technology and electronics industries where setup times depended on cumulative processing history for example, electronic components requiring restoration due to prolonged exposure to electromagnetic fields. The study applied the scheduling model to capture this past-sequence-dependent behaviour, enabling more accurate planning of setup and processing operations. This application was particularly relevant in labour-intensive production and service settings, allowing managers to account for productivity gains over time and incorporation of resource allocation decisions such as energy, manpower or financial inputs supports practical trade-offs between operational speed and resource consumption. The study could be applied directly to customer-centric operations such as repair services, healthcare scheduling, and call centers, where minimizing disparities in service completion was essential. The study further extended its application by considering rate-modifying activities, representing maintenance, calibration or system upgrades. The study demonstrated that complex real-world scheduling environments could be optimized efficiently while simultaneously accounting for human behaviour, resource costs and operational constraints. The polynomial-time solutions made the application not only theoretically sound but also computationally feasible for practical implementation. Watekar [28] in 2017 presented an application on optimization of job scheduling in manufacturing and production systems. The deviation technique was applied to classical flow shop scheduling problems, where multiple jobs must be processed sequentially on multiple machines. The study demonstrated the application across three practical scenarios n jobs on two machines, n

jobs on three machines and n jobs on m machines. Through numerical examples, the paper applied the technique to determine optimal job sequences that reduced the overall completion time of all jobs. This application was particularly relevant in manufacturing systems where reducing makespan directly improved machine utilization, throughput and delivery performance. The proposed method was applied to compute idle times for each machine after sequencing. By presenting machine-wise idle times, the study demonstrated that the deviation technique could be used as a capacity utilization tool, helping managers to identify inefficiencies and underutilized resources in production lines. The application of the study was that the deviation technique could work for multi-machine problems without reducing them to two-machine equivalents. The study was strengthened by the clear procedural steps used to implement the deviation technique calculation of row and column deviations, identification of zero-deviation cells and logical placement of jobs in the sequence and iterative reduction of the problem. The study applied the technique using well-structured numerical examples for two, three and multi-machine cases. These examples simulated realistic job-processing environments and clearly demonstrated how the technique leads to feasible and efficient job sequences. This practical demonstration enhanced the credibility and applicability of the proposed method. While empirical validation was limited, the application effectively demonstrated the potential to improve time efficiency and machine utilization, making it a meaningful contribution to applied operations research.

Inventory management is applied to control the ordering, storage, and usage of goods so that demand is met at minimum cost. It helps organizations reduce holding, ordering and shortage costs while ensuring smooth production and service operations. Blackstone and Cox [5] applied inventory management techniques to illustrate that the organizations could control stock levels, reduce costs and improve operational efficiency. Rather than proposing new models, the application demonstrated the practical relevance of established inventory techniques in business environments, especially for manufacturing and trading organizations. The study used inventory classification methods, particularly ABC analysis, VED analysis and HML and FSN classifications. These techniques were applied to categorize inventory based on value, criticality, consumption rate and movement. The application showed that the management attention could be focused on high-value or critical items, while routine control could be applied to less important stock items. This practical segmentation supported better decision-making and efficient resource allocation. By applying inventory management techniques excess inventory and holding costs were reduced, stock-outs and emergency procurement were minimized and capital was freed for other operational needs. The study applied inventory techniques as managerial control instruments enabling better planning and forecasting, improved coordination between purchasing, production and sales and timely decision-making based on inventory status. Strengths of the study were demonstrating practical usability of inventory techniques, integrating multiple techniques for comprehensive control, emphasizing cost and efficiency benefits and suitability for small, medium, and large organizations. Limitations of the study were limited empirical or case data, assuming stable demand and lead times in some techniques and limited discussion on implementation challenges. Although largely descriptive, the application reinforced the continuing relevance

of classical inventory tools in practical business settings. In 2011 Abdurraheem et al [2] did empirical examination of inventory management as a determinant of profitability in small businesses by applying financial and econometric tools to test whether effective inventory management translated to improved business performance. The study was quantitative and empirical, based on actual inventory (stock) values, profit data from six small businesses and a 10-year time horizon. A very high correlation coefficient ($R = 0.915$) indicated that about 84% of variation in profit and a t-value of 6.409, showing strong statistical significance. The empirical study successfully showed that a ₦1 change in inventory value lead to approximately ₦0.91 change in profitability so inventory management had a strong positive and economically meaningful impact on SME profitability and poor inventory control could directly threaten business survival. The applied results were translated into managerial implications, such as need for systematic stock checking and record keeping, importance of avoiding stock-outs and overstocking and link between inventory control and working capital efficiency was established. Strengths of the study were use of real financial data from operating small businesses, longitudinal (10-year) data improved reliability, simple and transparent econometric application and strong statistical evidence supporting conclusions. Limitations of the study were measuring inventory management only by inventory value, not by advanced techniques, using bivariate model and using small sample size. By applying regression analysis to real SME data, the study demonstrated that inventory management played a critical role in small business profitability. Hedrick et al [11] applied inventory management as a managerial decision-making and control function, emphasizing everyday operational realities such as purchasing, stock handling, storage and record keeping. The study was applied not merely as physical stock but as capital tied up in business operations as poor inventory control directly lead to cash flow problems, increased holding costs, obsolescence and waste and reduced profitability. The study applied inventory management through a structured purchasing plan, emphasizing timing of orders, coordination with seasonal demand, planning inventory build-up and depletion and avoidance of panic buying. One of the strongest applications was the presentation of graduated inventory control methods, ranging from simple to advanced which allowed businesses to adopt inventory control methods that match their size, complexity and resources, making the recommendations realistic and scalable. The study applied basic quantitative tools as decision aids, not as rigid optimization models, reinforcing their usability for small business managers with limited technical expertise. The study extended its application to more advanced systems, including material requirements planning (MRP), Just-In-Time (JIT) and kanban systems. Strengths of the study were highly practical and implementation-oriented, tailored to small business realities and scalable from manual to computerized systems. Limitations of the study were limited empirical or case-based validation, limited treatment of stochastic demand and uncertainty and not quantifying cost savings from recommended practices. The paper effectively equipped small business owners with practical tools to improve efficiency, reduce costs and enhance profitability. In 2016 Kanguru [16] applied inventory management principles to small, medium and micro enterprises (SMMEs) operating in the Cape Metropole, South Africa. The study was motivated by the high failure rate of SMMEs and the

recognition that ineffective inventory control was a major contributor to poor financial performance. Rather than developing new inventory models, the study applied established inventory practices to assess their use in SMMEs in a real economic environment. It was revealed that most SMMEs relied on manual systems and informal procedures, reflecting resource constraints and limited managerial expertise. The study applied a survey-based quantitative approach to collect data from SMME owners and managers using structured questionnaires, while business performance were assessed through indicators such as sales growth, cost control and stock availability. The study found that the many SMMEs did not use formal inventory control techniques such as EOQ or computerized systems, poor record keeping lead to frequent stock-outs and overstocking and businesses that applied basic inventory controls consistently performed better operationally. It was recommended to train SMME owners in basic inventory control techniques, adopt affordable inventory software and integrate inventory planning with financial management. Some strength were focusing on practical inventory practices rather than abstract models, providing policy-relevant insights for enterprise development agencies and reflecting operational constraints faced by small businesses. Although the study relied on self-reported data, did not quantify financial gains from improved inventory practices and used limited advanced inventory optimization models yet it highlighted the critical role of basic inventory control in improving operational efficiency and sustainability. Islam et al [13] in 2019 presented a practical application of inventory management analysis tools to diagnose and improve inventory efficiency in a Small and Medium Enterprise (SME) operating in the heavy equipment spare parts industry. The main purpose of the study was to identify the root causes of inventory mismanagement that lead to slow-moving and excess stock, delivery delays and high inventory holding costs which reduced profitability. The application demonstrated that a small number of spare-part categories for example engine parts, seals, filters accounted for a disproportionate share of inventory inefficiency, validating the Pareto principle in a real SME context. The fishbone diagram was applied to systematically identify non-quantitative causes of inventory inefficiency. The study categorized root causes into six dimensions people, process, equipment, material, environment and management. The study was strengthened through direct observation and interviews with managers and supervisors involved in inventory operations. It was found that there was lack of trained inventory personnel, absence of standard operating procedures and manual and unintegrated information systems were used. The applied methodology successfully identified two dominant causes of inefficiency unintegrated inventory information systems and inadequate human resource capability in inventory management. The study was strengthened by conducting in a real SME environment, by integrating quantitative and qualitative methods, by using simple, industry-relevant tools and by identifying practical improvement areas. Limitations of study were not determining optimal order quantities or reorder points, lacking cost-based optimization analysis and study basing on single case study. The study provided a valuable applied framework for inventory efficiency analysis, particularly for SMEs lacking advanced inventory optimization systems. Orobia and Nakibuuka [20]in 2020 applied inventory management concepts to real operational environment of small businesses in Uganda which

was characterized by informal systems, limited resources, and high business failure rates. The study was applied as a set of day-to-day managerial practices rather than advanced quantitative models which included planning when and how much inventory to stock, recording inventory purchases, monitoring stock levels, controlling access to storage facilities and checking inventory conditions to avoid losses. Managerial competence was applied through three practical dimensions knowledge skills and ability in decision-making and task execution which were measured using perception-based survey items that captured how managers actually performed inventory-related tasks. The study applied this framework to show that managerial competence improved financial performance partly through better inventory management and inventory management accounted for nearly 50% of the total effect. It was found that businesses with competent managers had experienced fewer stock-outs and overstocking problems, reduced inventory-related losses such as spoilage and obsolescence and achieved better sales continuity and profitability. Using behavioural measures suited to informal businesses, demonstrating a clear causal pathway and highly relevance for capacity-building programs were some strengths of the study. Limitations of the study were not testing specific inventory optimization models, not auditing objectively and context-specific study. The study made a valuable contribution by showing that improving skills and knowledge could significantly enhanced inventory practices and financial performance in small businesses. Immaculate et al [12] in 2020 focused on implementing key inventory management techniques like ABC analysis, EOQ calculation, safety stock determination and inventory turnover ratio to evaluate inventory performance in Reliance Retail Limited, Chennai. The aim of the study was to assess efficiency level in which inventories were maintained, to uncover issues like overstocking, stock-outs, or inconsistent ordering, to estimate optimal order quantity, to classify items based on value significance and to evaluate how turnover changed over five years. The study used secondary data from turnover statements, monthly inventory statements, retail shop records and direct interactions with employees to evaluate 40 items. It was found that A-items were having 80.26% of consumption value, B-items were having 15.31% of value and C-items were at 4.43% of value. EOQ was computed for all selected items and compared with current ordering practices and it was found that organization did not follow EOQ and orders were placed frequently with small quantities. The study calculated the turnover ratio for five years (2014–2019) which was increased from 28.09 to 1253.03. The study of these techniques led to several insights inventory turnover improving indicated efficient inventory movement, safety stock calculations showed well-maintained reserve levels and ABC analysis helped to understand the need for tighter control of A-items. It was found that current system lacked structured inventory control, ordering was ad-hoc, not EOQ-based, did not differentiated control among A/B/C categories and overstock and stock-out issues were common due to absence of systematic techniques. Using ABC, EOQ, safety stock and turnover ratio created a multidimensional evaluation and ending the application with some practical suggestions such as adopting JIT and strengthening controls for A-items were some strengths of the study. Lacking cost details for EOQ, using small sample size and not applying forecasting method

were some limitations of the study. The study successfully demonstrated the use of classical inventory techniques to diagnose operational inefficiencies and improve stock management.

Conclusion

This paper emphasizes the importance of Operations Research techniques in addressing practical problems across diverse fields. The applications of queuing, graph theory, replacement, inventory control and scheduling demonstrate how mathematical models can significantly improve efficiency, reduce costs, and enhance decision-making. Overall, Operations Research serves as a powerful tool for optimizing complex systems and supports organizations in achieving effective and sustainable operational performance.

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