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BCA Honours | Semester II | BCA2CJ103

Numerical Analysis and Operations Research

Module 4 Comprehensive Notes

Module 4: Transportation, Assignment, and Project Network Analysis

Specialized linear programming formulations address logistics distribution and task assignments with high computational efficiency. Project management methodologies structure inter-dependent activities into critical network paths.

4.1 The Transportation Problem (TP)

A transportation problem coordinates distributing a homogeneous commodity from m origins (sources with supplies a_i) to n destinations (sinks with demands b_j) at minimum aggregate transit cost $\sum_{i=1}^{m}\sum_{j=1}^{n} c_{ij}x_{ij}$. A transportation problem is balanced if total supply equals total demand: $\sum_{i=1}^{m} a_i = \sum_{j=1}^{n} b_j$.

Methods for Finding an Initial Basic Feasible Solution (IBFS)

- **North-West Corner Rule (NWCR):** Strictly allocates capacity beginning at the top-left cell $(1, 1)$, advancing rightward or downward as supply or demand is satisfied. Simple to execute, but ignores unit transportation costs c_{ij}, yielding a relatively high-cost initial solution.
- **Least Cost Method (LCM):** Greedily prioritizes cells with the lowest per-unit transit cost c_{ij} across the entire cost matrix, improving initial cost efficiency.
- **Vogel's Approximation Method (VAM):** Computes penalty costs for each row and column (the difference between the two smallest per-unit costs). Selects the row or column with the largest penalty and allocates maximum capacity to its lowest-cost cell. VAM consistently yields an IBFS very close to the global optimum.

Optimality Test via MODI Method ($u - v$ Method)

For an initial solution with $m + n - 1$ occupied basic cells without cycles:

1. Set dual variables $u_i + v_j = c_{ij}$ for all allocated basic cells (setting arbitrary $u_1 = 0$).
2. Evaluate opportunity costs for all unoccupied cells: $\Delta_{ij} = c_{ij} - (u_i + v_j)$.
3. If all Δ_{ij}
   ≥ 0, the allocation is optimal. If any Δij < 0" style="color:#cc0000">Δ_{ij} < 0, construct a closed stepping-stone loop to reallocate flow around the most negative opportunity cell.

4.2 The Assignment Problem and the Hungarian Algorithm

The assignment problem allocates n distinct facilities or workers to n tasks on a strict one-to-one basis to minimize total completion cost. The governing mathematical matrix is represented by cost matrix $C = [c_{ij}]$ where decision variables are binary: $x_{ij} \in \{0, 1\}$.

The **Hungarian Method** (Kuhn-Munkres algorithm) solves the assignment problem in $O(n^3)$ polynomial time:

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1. **Row Reduction:** Subtract the minimum element of each row from all elements in that row.
2. **Column Reduction:** Subtract the minimum element of each column from all elements in that column.
3. **Zero Covering:** Draw the minimum number of horizontal and vertical lines to cover all zeros in the matrix. If lines drawn equal matrix order n, an optimal zero assignment exists.
4. **Augmentation:** If lines k < n, locate the smallest uncovered element d. Subtract d from all uncovered cells, and add d to all cells at line intersections. Repeat line covering.

4.3 Project Network Analysis: CPM and PERT

Complex software engineering projects require scheduling inter-dependent activities subject to precedence constraints.

Evaluation Dimension	Critical Path Method (CPM)	Program Evaluation & Review Technique (PERT)
Activity Duration Nature	Deterministic (known with empirical certainty).	Probabilistic (modeled via Beta distribution under uncertainty).
Time Estimates per Activity	Single deterministic duration estimate.	Three estimates: Optimistic (a), Most Likely (m), Pessimistic (b).
Expected Duration Formula	T = Duration	$t_e = \frac{a+4m+b}{6}$, $\sigma^2 = \left(\frac{b-a}{6}\right)^2$
Critical Path Definition	Longest continuous sequence of linked activities with zero total float. Determines project completion time.	Path with maximum expected completion time and cumulative path variance.

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1. Architectural Trade-offs and Computational Complexity

Software architects and systems engineers designing scalable computational pipelines centered on Numerical Analysis and Operations Research must methodically navigate core trade-offs:

- **Time Complexity Optimization versus Spatial Footprint:** In high-throughput algorithmic pipelines handling Module 4 Core Concepts and Methods, pre-computing intermediate lookup tables, spatial indices, and hashing structures achieves near-instantaneous O(1) query latency, but inflates the physical memory footprint. Conversely, in-place algorithms minimize RAM utilization at

the cost of higher CPU cycle counts. Modern architectures dynamically calibrate memory allocations using memory-mapped files and cache-aware structures.

- **Concurrency Scalability versus Thread Contention:** While multi-core hardware allows horizontal execution, concurrent modifications to shared state structures create severe lock contention, thread synchronization bottlenecks, and cache line invalidation storms. High-performance frameworks deploy lock-free algorithms, optimistic concurrency control, and atomic compare-and-swap (CAS) primitives.
- **Algorithmic Determinism versus Heuristic Scalability:** Exact mathematical algorithms frequently encounter NP-hard combinatorial barriers as problem dimensions scale. Contemporary systems bridge this gap by deploying bounded approximation algorithms and meta-heuristics that produce near-optimal solutions within guaranteed execution time windows.

2. Empirical Comparative Framework

A structured comparative assessment clarifies operational distinctions across conventional paradigms and modern production implementations in Numerical Analysis and Operations Research:

Evaluation Dimension	Conventional Traditional Approach	Contemporary Integrated Paradigm	Strategic Impact Metric
Architecture Paradigm	Monolithic single-threaded architectures with tightly coupled state.	Distributed microservices with asynchronous event queues and thread-safe data structures.	Linear scalability and resilient fault isolation under peak transactional loads.
Data Processing Pipeline	Synchronous batch processing characterized by high latency and scheduled processing windows.	Real-time streaming pipelines with sub-second event ingestion and processing.	Zero-latency decision intelligence and immediate anomaly response.
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System Telemetry & Auditing	Passive log file aggregation with retrospective forensic analysis.	Distributed tracing, structured metrics collection, and real-time observability telemetry.	Proactive bottleneck resolution and sub-second mean time to detection (MTTD).

3. Production Implementation Patterns and Resilience Engineering

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- **State Immutability and Event Sourcing:** Maintaining an append-only log of immutable state changes guarantees verifiable auditability, eliminates data race hazards, and facilitates seamless

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- **Defensive Memory Management:** High-throughput applications implement strict resource pools, bounded buffer queues, and proactive leak detection to ensure predictable garbage collection pause t × and prevent memory exhaustion.

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